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LLNL-PRES-499357

Experimental overview of ELM control using external magnetic perturbations

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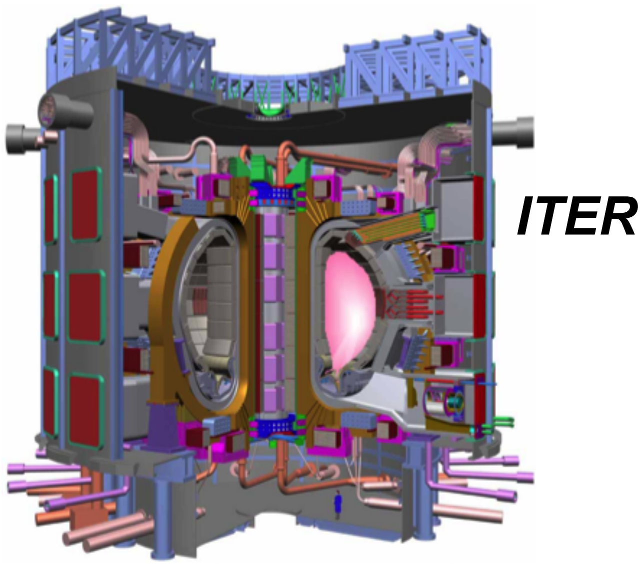
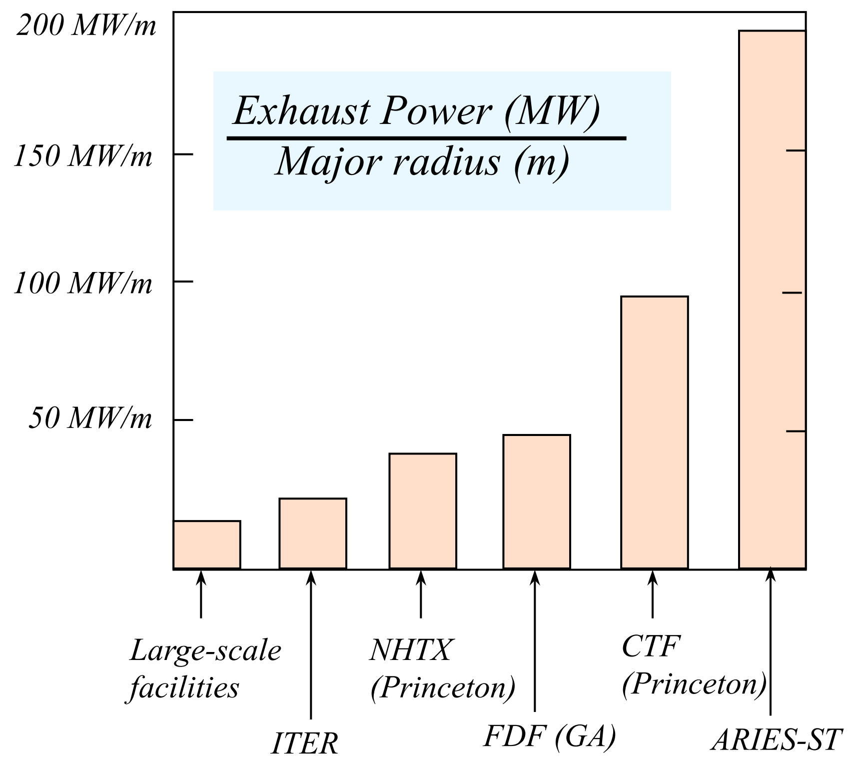
13th International Workshop on Plasma Edge Theory
South Lake Tahoe
September 19th, 2011

BURNING PROBLEM: Next-generation tokamak reactors desperately need techniques to reduce heat fluxes

- Tokamak performance has reached the level where heat flux poses an issue
  - The steady-state divertor heat load in ITER is only marginally manageable

- Transient "bursty" events greatly increase damage to divertor & first wall
  - ITER has no tolerance for ELMs





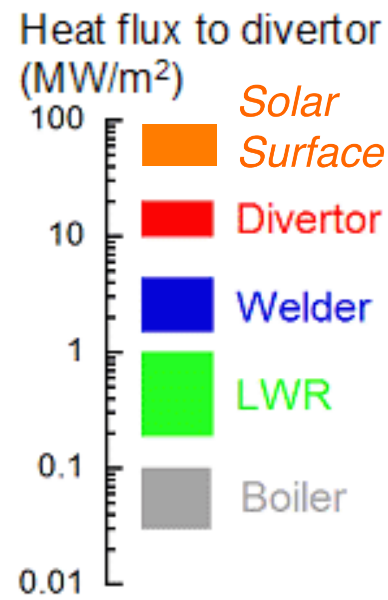
- ***These issues becomes increasingly difficult for next-step devices!***

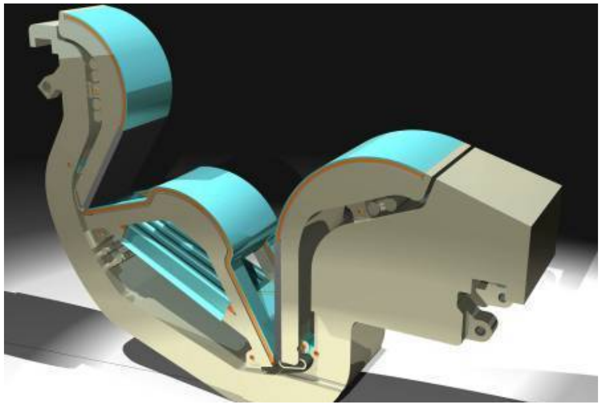
Exhaust power must be limited to acceptable levels for divertor target plate materials

- **Steady-state limit for continuous heating**
  - Constrained by target plate material phase transition C (sublimation) or W (melting)
    - Heat flux Q < 10 MW/m^2

- **Transient limits for bursts of heat more stringent**
  - Constrained by target plate heat conduction
    - Heat impulse Q $\tau^{1/2}$ < 35-50 MJ s$^{1/2}$/m^2

- **Unfortunately, bursty transport is ubiquitous**
  - Prediction for type-I ELMs on ITER at ν^*=0.6
    - $\Delta W_{ELM} \sim 20$ MJ [Loarte, 2003]
  - But, limits have decreased as research continues
    - $\Delta W_{ELM} < 1$ MJ [Federici 2006]
    - $\Delta W_{ELM} < 0.2$ MJ [Pitts EPS 2011]





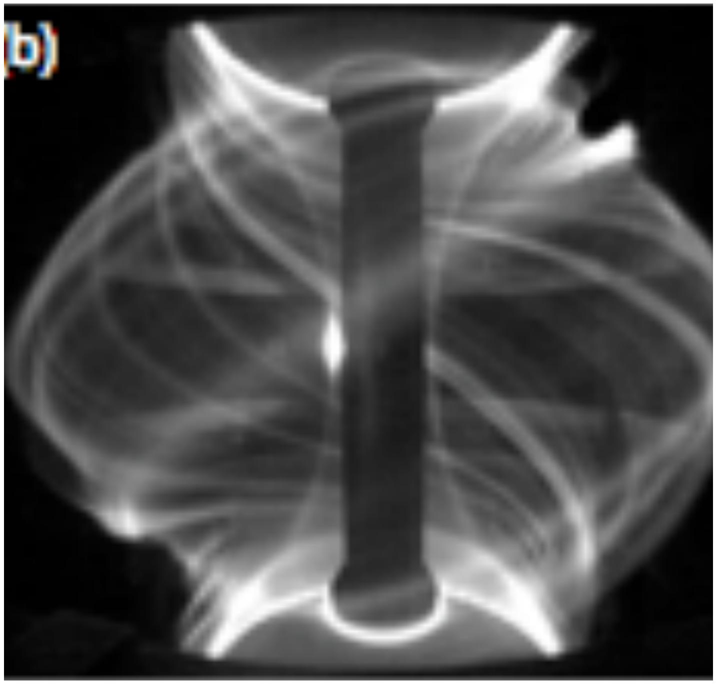
ITER divertor target cassette CFC tiles & W armor

At least three different flavors of ELM control exist

1. **ELM suppression**
   - **No discernable ELMs remain**
   - **Low collisionality threshold**

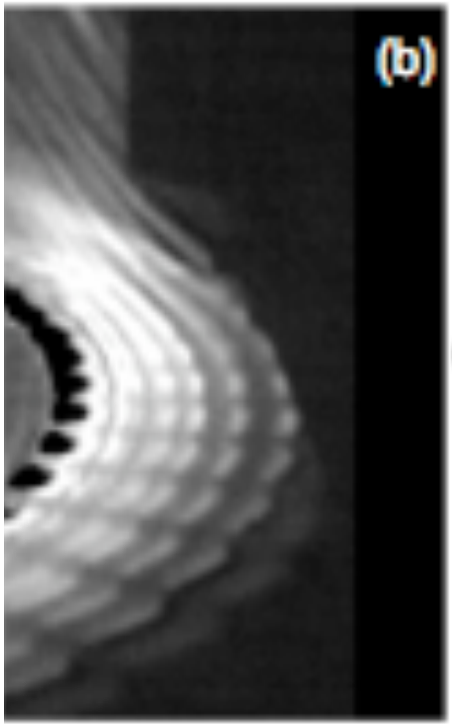
2. **ELM mitigation**
   - **Small ELMs remain (prob. not type-I)**
   - **High-collisionality threshold?**

3. **ELM triggering**
   - **Used to control impurity transport in ELM-free regimes**



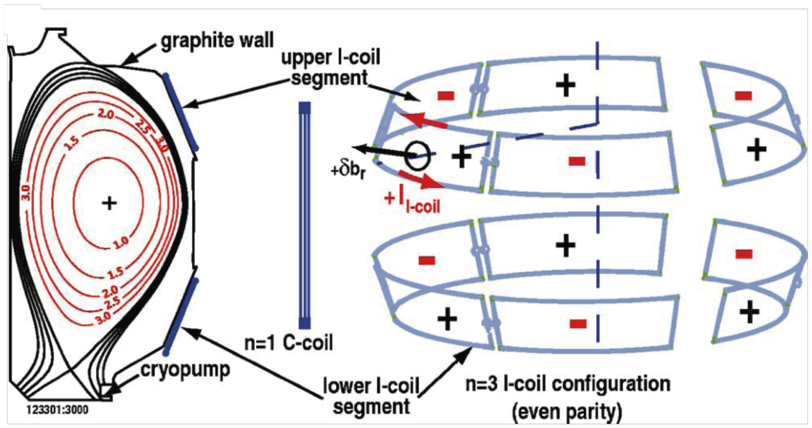
ELM in Dα on MAST tokamak
*A. Kirk, Plasma Phys. Control. Nucl. Fusion, **49** 1259 (2004)*

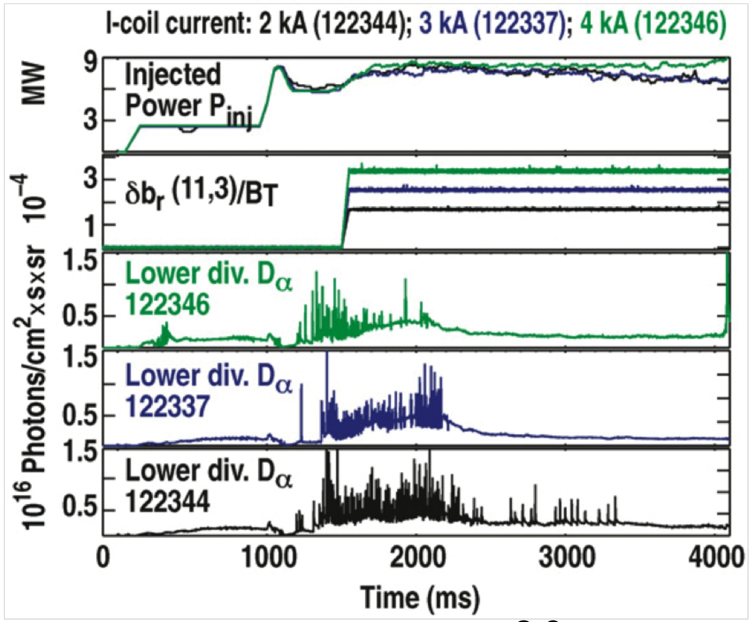
Recycling profile on target plates



DIII-D discovered that non-axisymmetric magnetic perturbations can stabilize ELMs … and destabilize ELMs

- **ELM mitigation first found on DIII-D H-mode plasmas[1]**
  - **Using external coils**

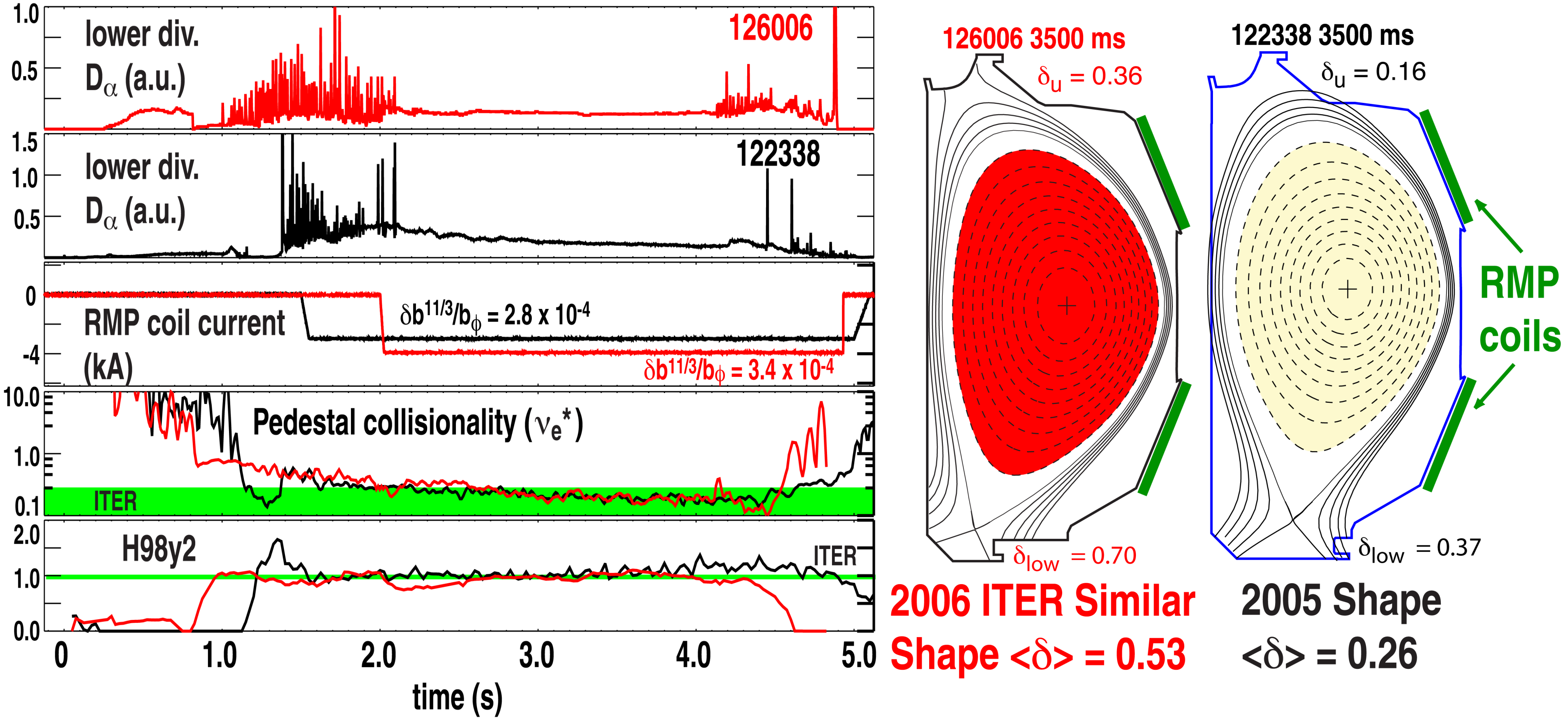




- **Full ELM suppression then discovered at low collisionality[2,3]**
  - **Threshold in perturbation amplitude**
    - $\delta B/B \sim 3\times10^{-3}$
  - **Threshold in pitch-resonant field $k_{\|} = (m - qn)/qR = 0$**
    - $\delta B_{m=qn}/B \sim 3\times10^{-4}$

[1]T.E. Evans, et al., Phys. Rev. Lett. **92** 235002 (2004)
[2]K.H. Burrell, et al., Plasma Phys. Control. Fusion **47** B37 (2005)
[3]T.E. Evans, et al., Nature Phys. **2** 419 (2006)

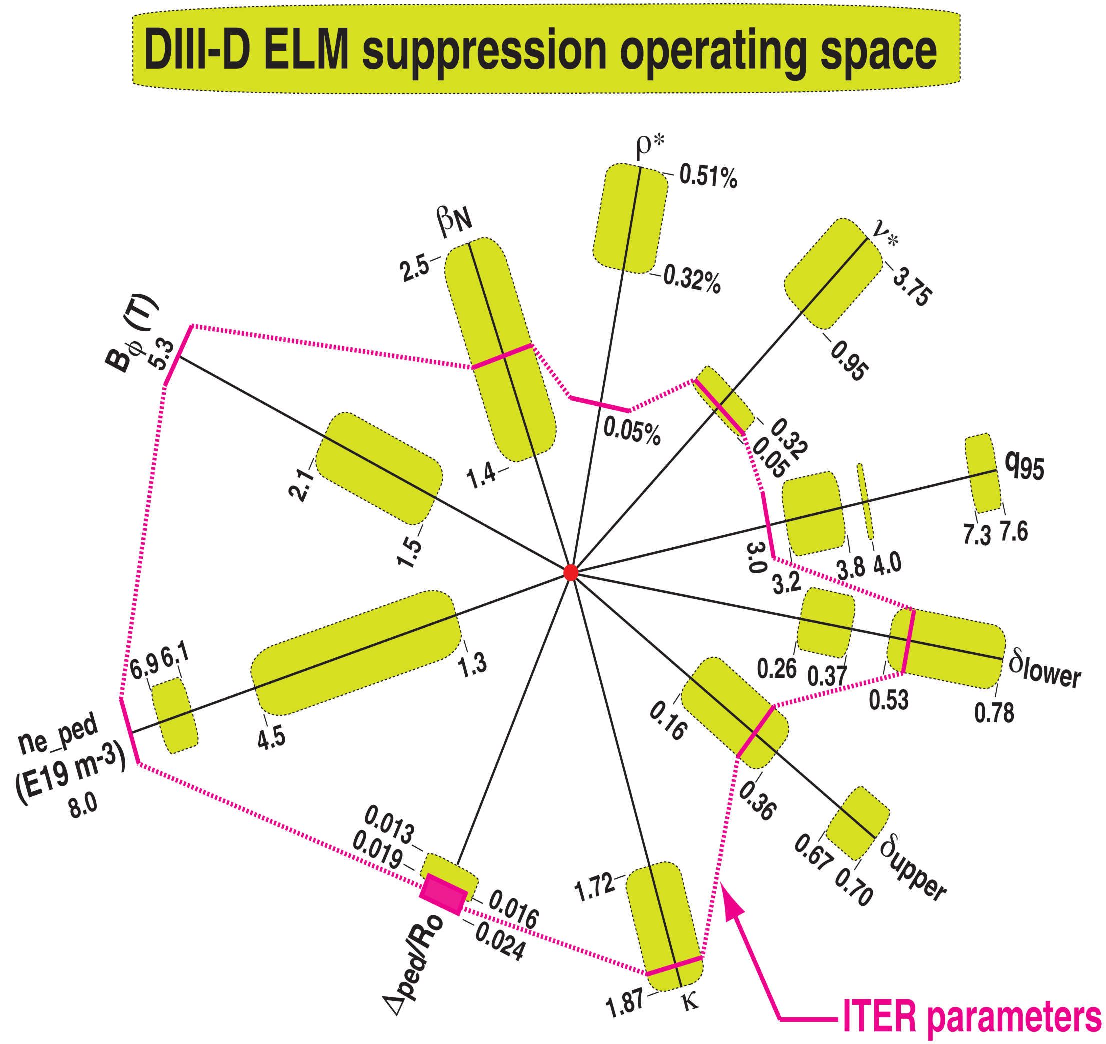
ELMs are Completely Eliminated with RMP Fields while Maintaining the ITER H-mode Confinement Target



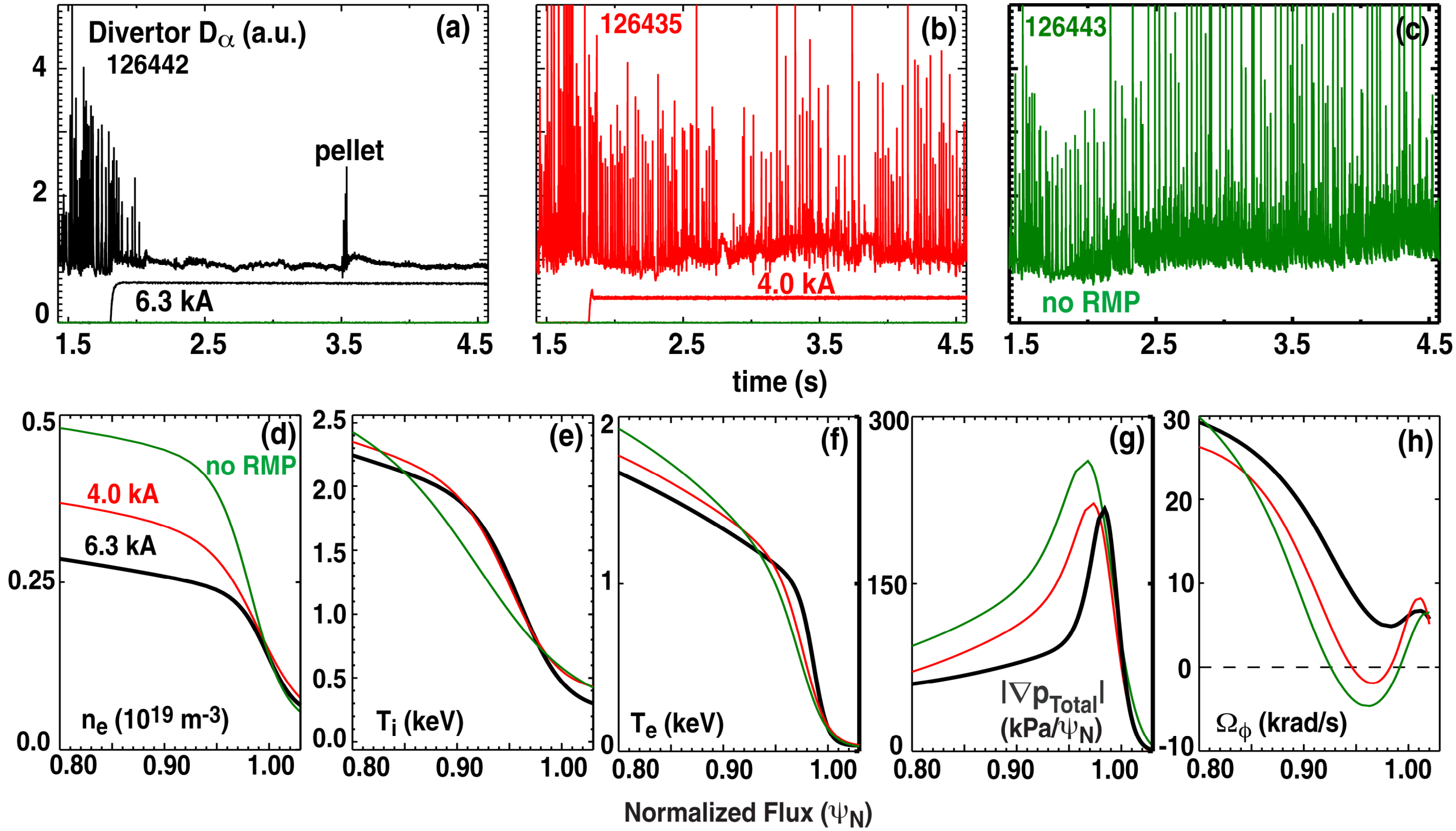
- Full suppression is obtained over a range of plasma shapes at an ITER pedestal collisionality

ELM Suppression is Obtained over a Wide Range of DIII-D Operating Parameters

- **RMP ELM suppression obtained with all key ITER dimensionless parameters**
    - Except for ρ* and q_{95}
- **ITER dimensional parameters such as B_ϕ, n_{e_ped} and are not accessible in DIII-D**
    - Models are needed to assess scaling to ITER



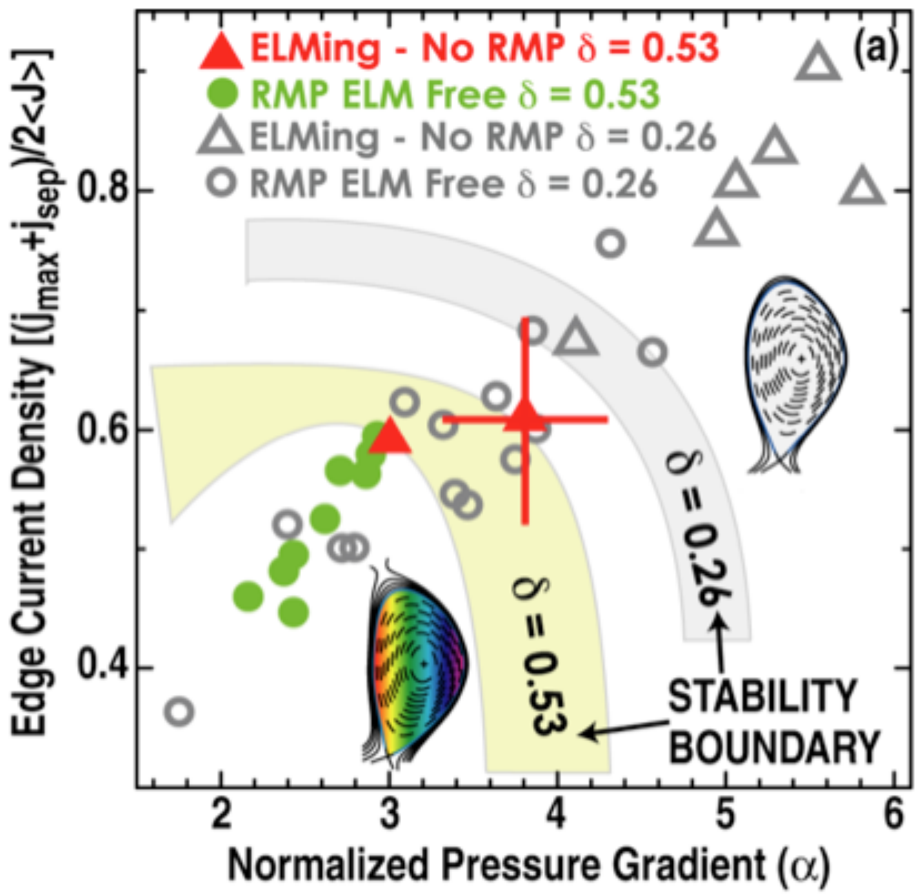
For ELM suppression at low-collisionality, the edge pressure is reduced via increased particle transport



[1]*T. E. Evans, et al., Nucl. Fusion* ***48*** *024002 (2008)*

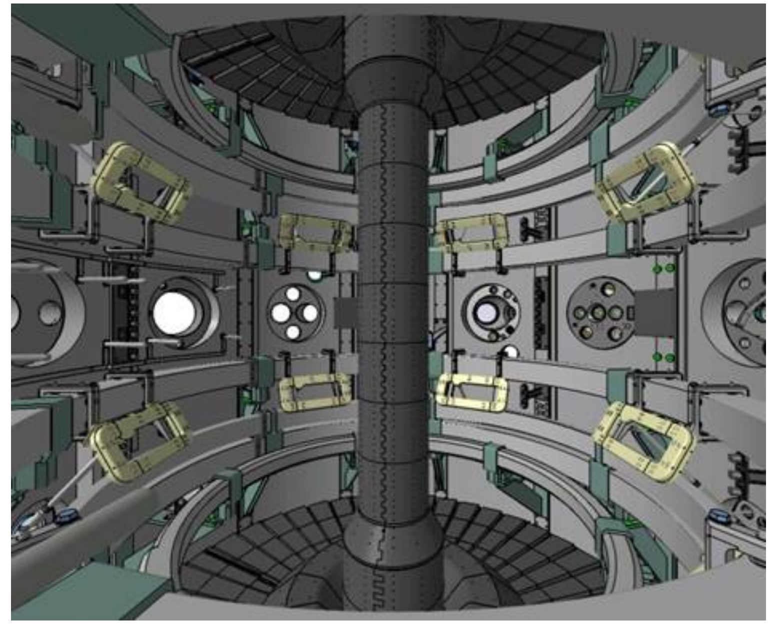
- Global n_e reduced as RMP increased (even in core)
- T_e and T_i actually increase in transport barrier region!

For low collisionality, reduction in edge ∇p & $J_{||}$ stabilizes type-I ELMs



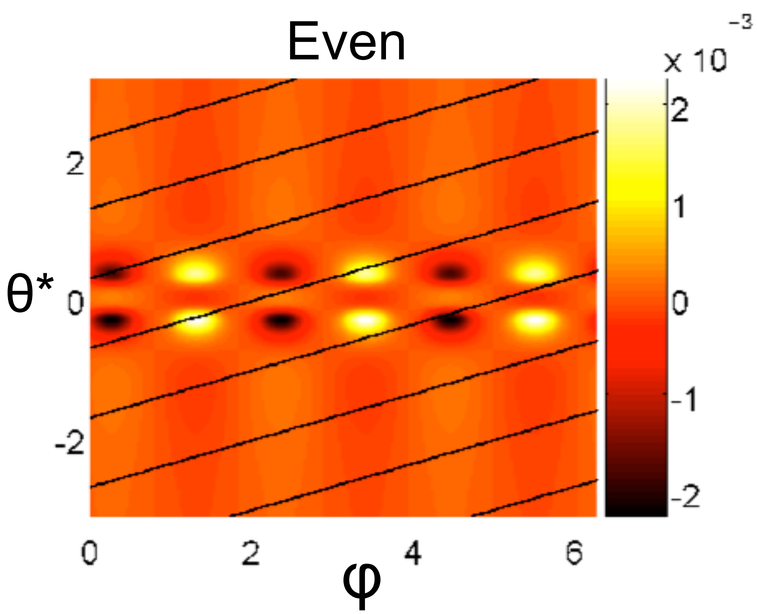
T. H. Osborne, et al., J. Phys.: Conf. Series A ***123*** *012014 (2008)*

The MAST ELM control coils

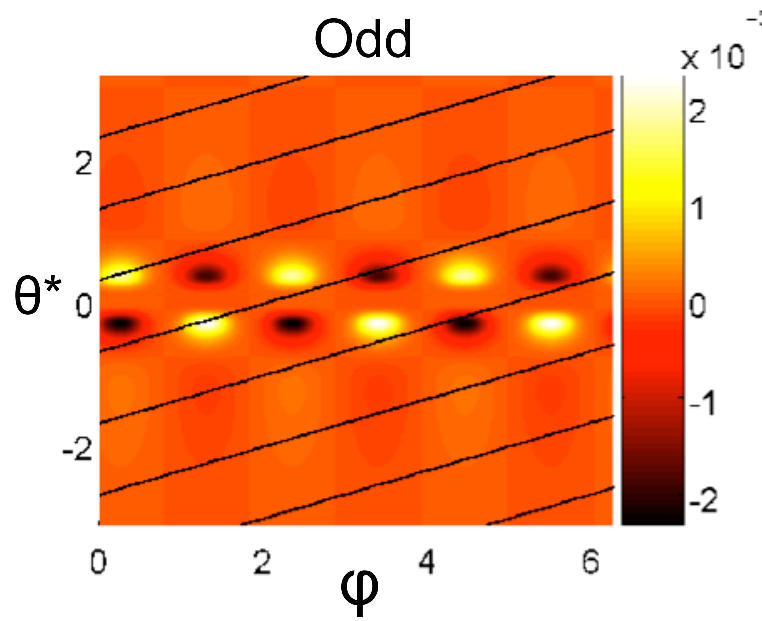


- 2 rows of 6 in-vessel coils, producing n=3 perturbations: similar to DIII-D I-coils
- Dimensioned so as to satisfy the Chirikov criterion $\Delta_{Chir>1}$>0.17
- Coils can carry up to 5.6kAt = 1.4kA x 4 turns
- Even and Odd configurations are possible
  - Complementary: when one is on resonance, the other is off resonance

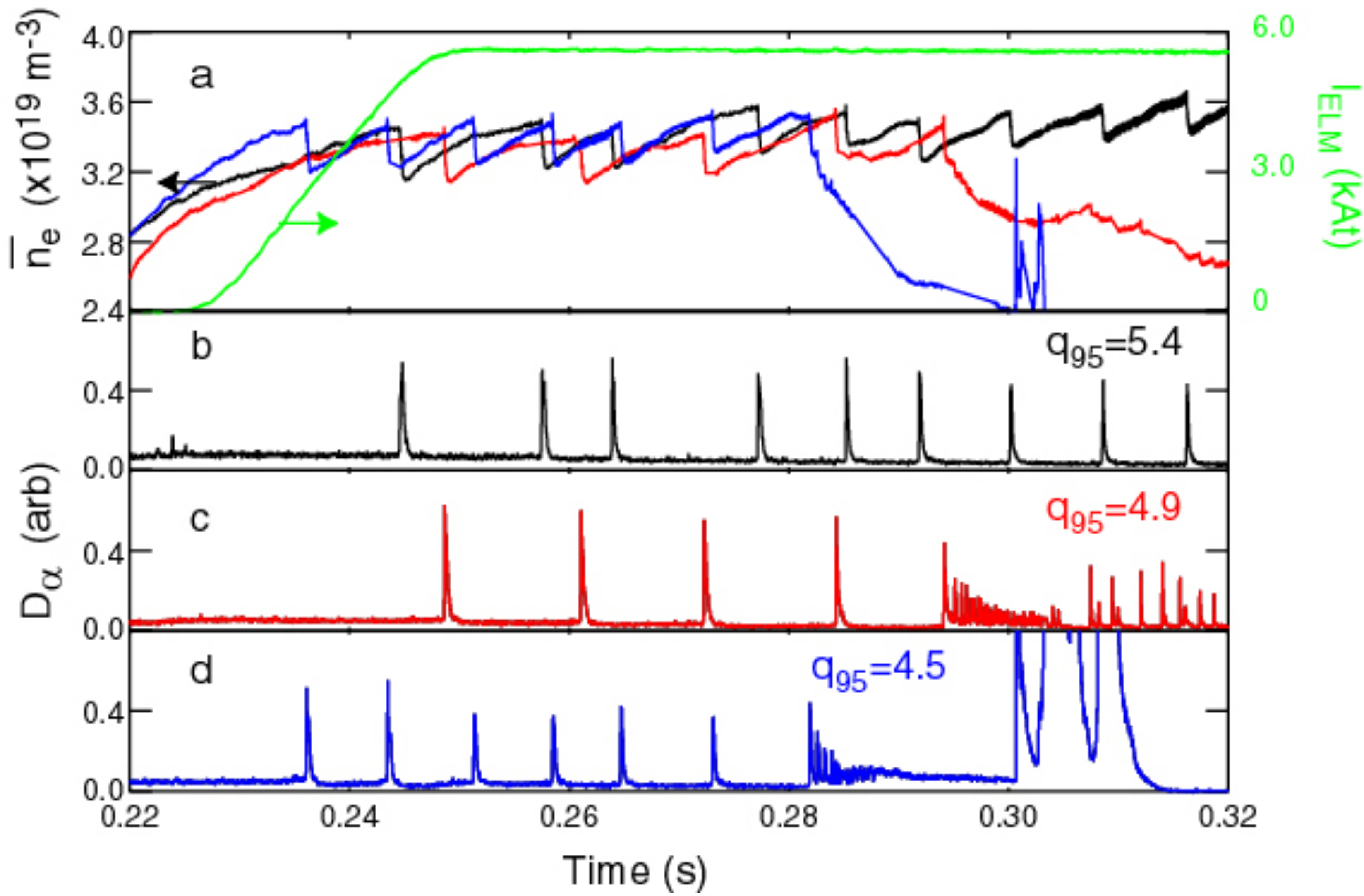
  $\Rightarrow$ Allows to test for resonant effects



B_r (T) on q=3
for 5.6kAt

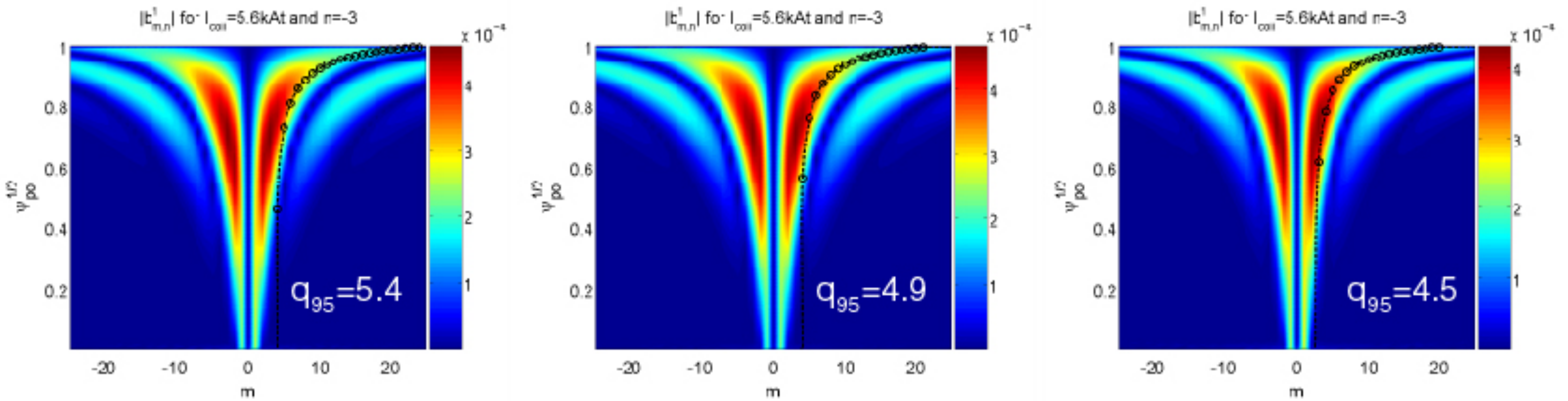


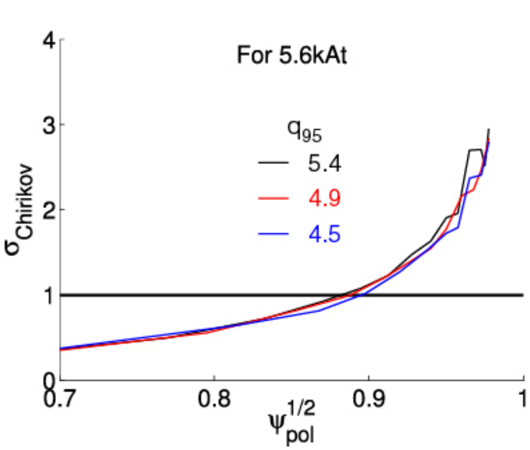
Effect on type I ELMs – q_{95} scan

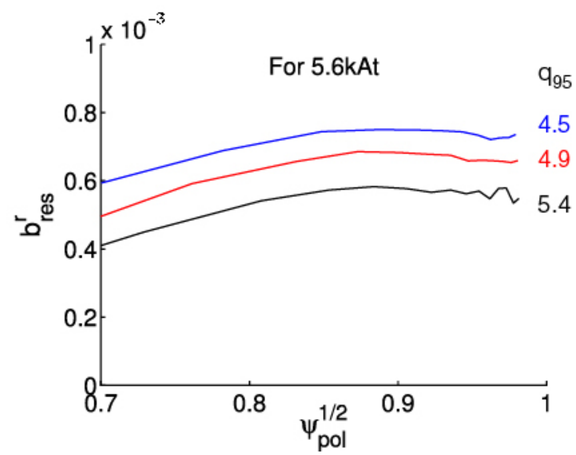


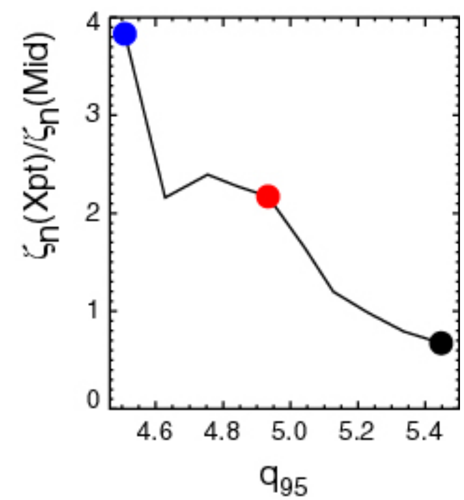
Back transition to L-mode seen at q_{95}~ 4.5

q_{95} scan - modelling









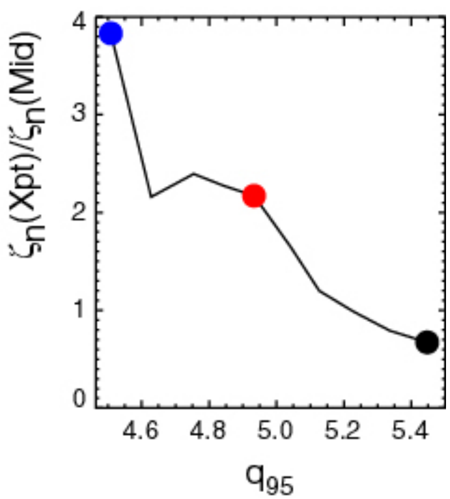
Little effect on $\Delta_{\Psi N\sigma chir>1}$ (≈0.19) – since decreasing q_{95} decreases island overlap due to changes in shear

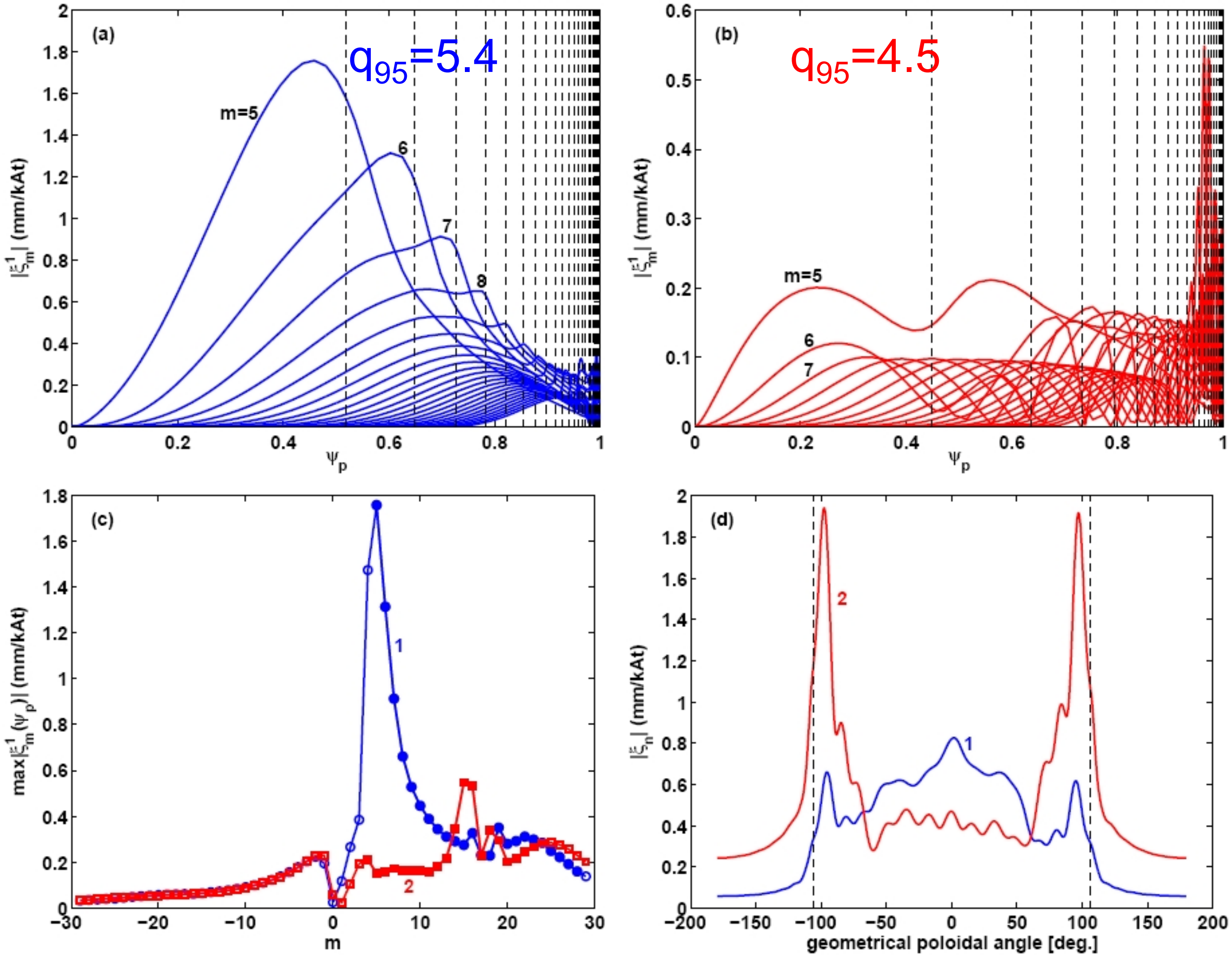
Field alignment improves → increase in resonant field (b^r_{res}) from 5.8 to 7.5x10^{-4}

Plasma displacement at the X-point also becomes more dominant (MARS-F)

X-point peaking and peeling mode

q95 = 5.4 compared to 4.5 for odd parity

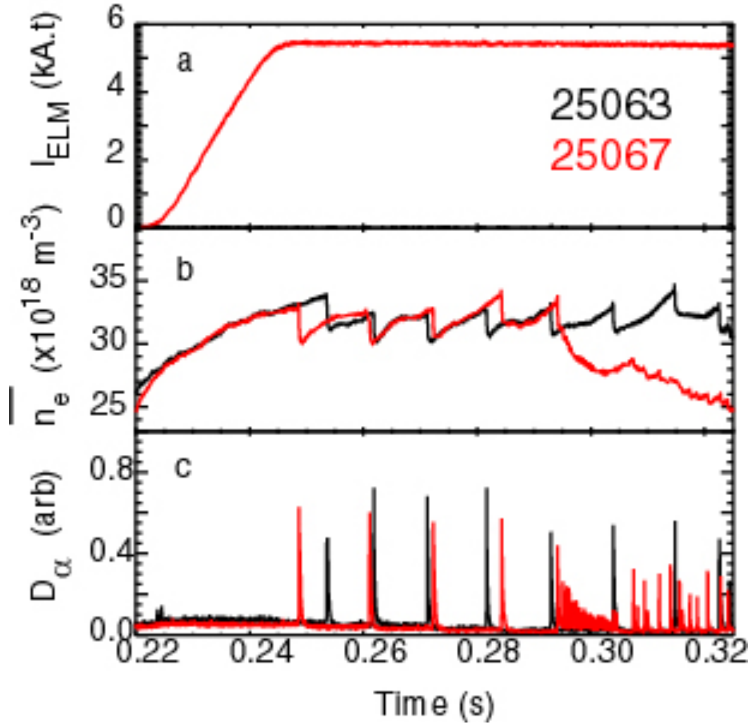




Plasma displacement at the X-point also becomes more dominant (MARS-F)

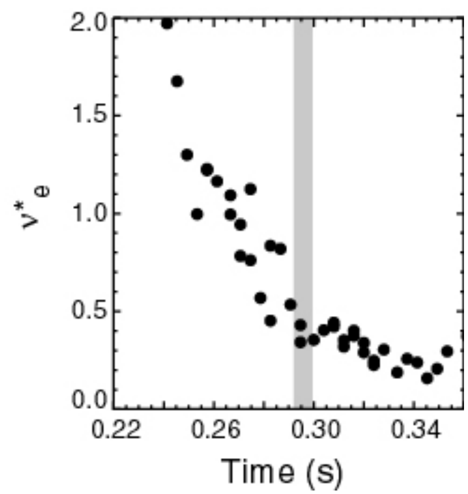
X-point peaking again associated with peeling mode becoming dominant

Effect of edge ν^*_e



Get clear pump out and effect on ELMs

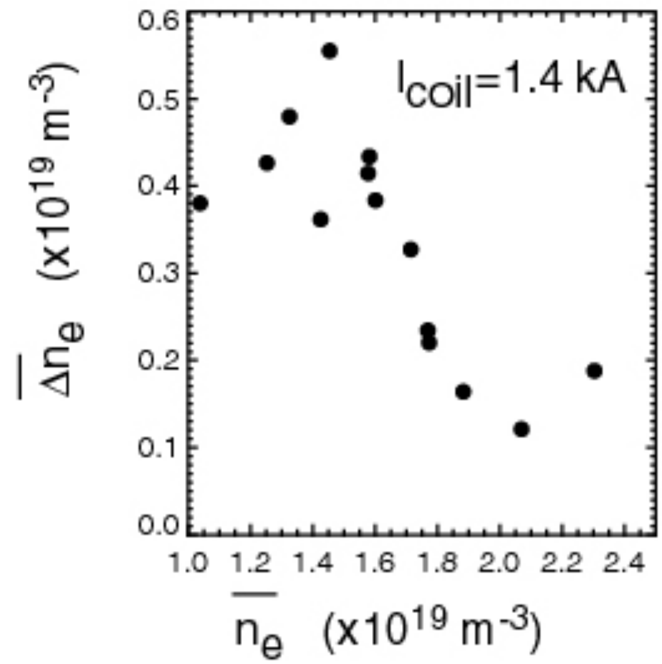
f_{ELM} increases by 5
ΔW_{ELM} reduces from 5 kJ to ~ 1kJ
W_{MHD} reduces by ~ 8%



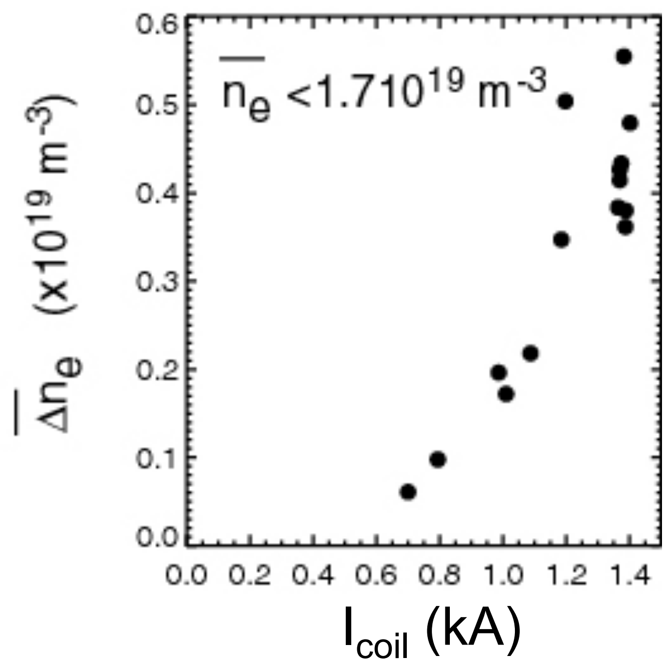
Pump out occurs when ν^*<0.5

L-mode results

➢ Pump-out trend with n_e and I_{coil}



• At full coils current (1.4kA), the pump-out decreases with density



• At moderate density (<1.7x10^{19}m^{-3}), the pump-out increases linearly with I_{coil}

– Offset suggests threshold

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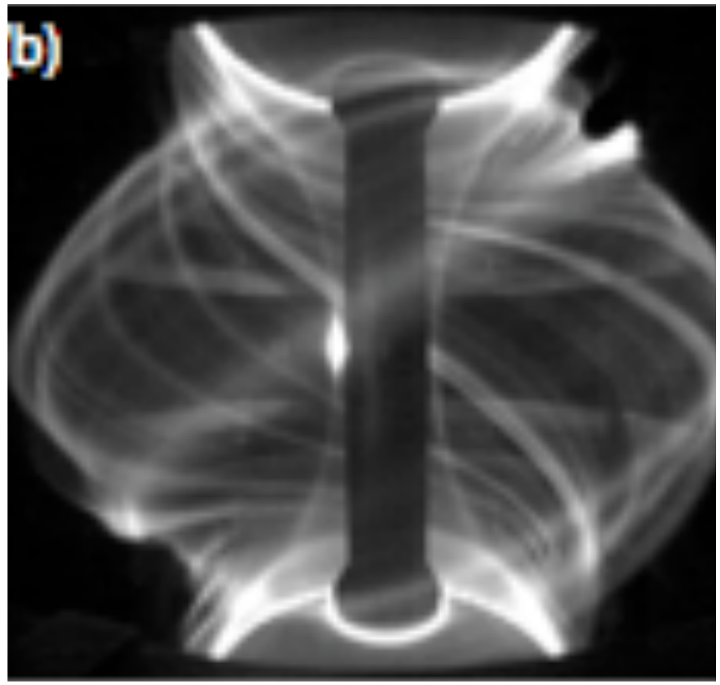

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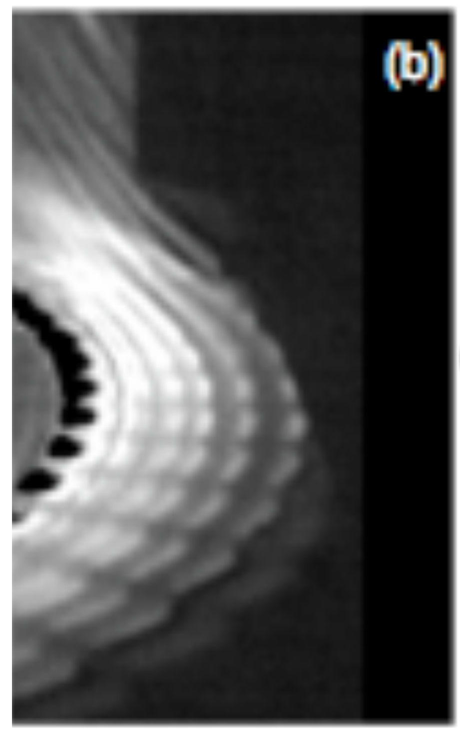
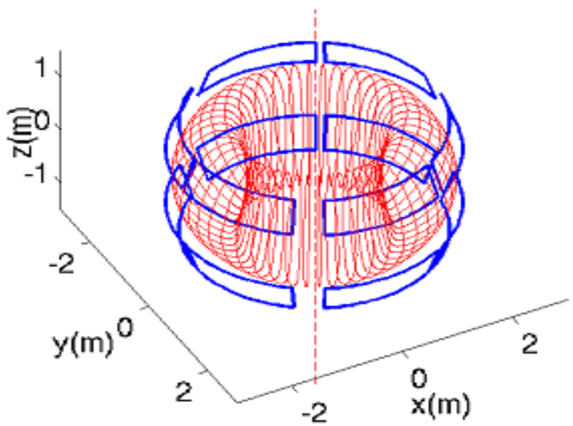


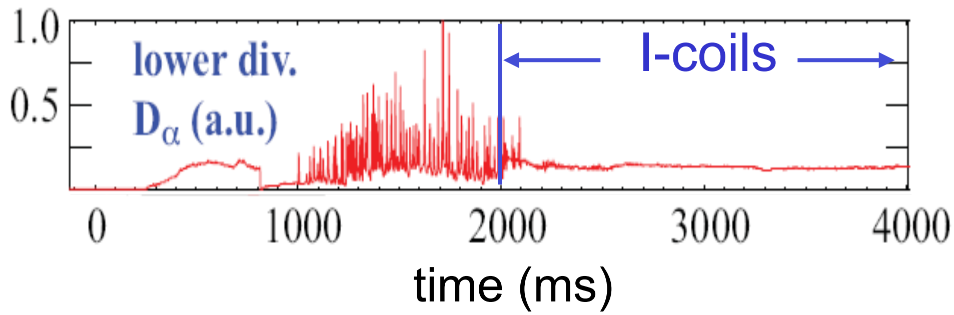
Background and motivation

- Type I ELMs are expected to be a factor 20 too large in ITER
- A candidate solution: Resonant Magnetic Perturbations (RMPs)
- Promising results on different machines:

ELM suppression on DIII-D

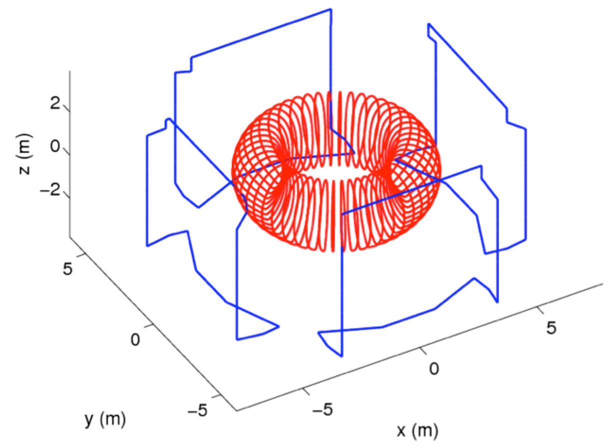


I-coils: 2 rows of 6 in-vessel coils, n=3

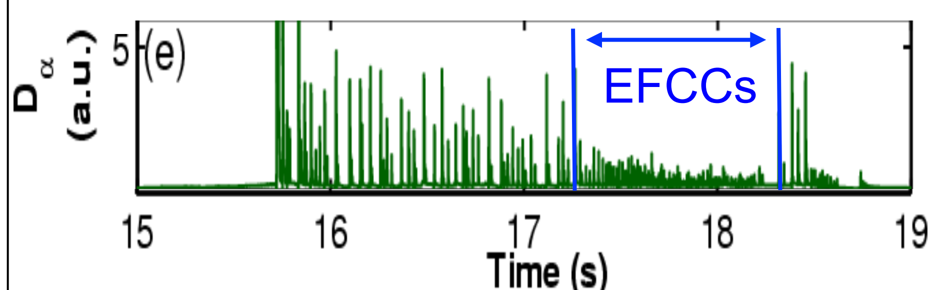


ELM mitigation on JET

Y. Liang, O5.062 on Friday

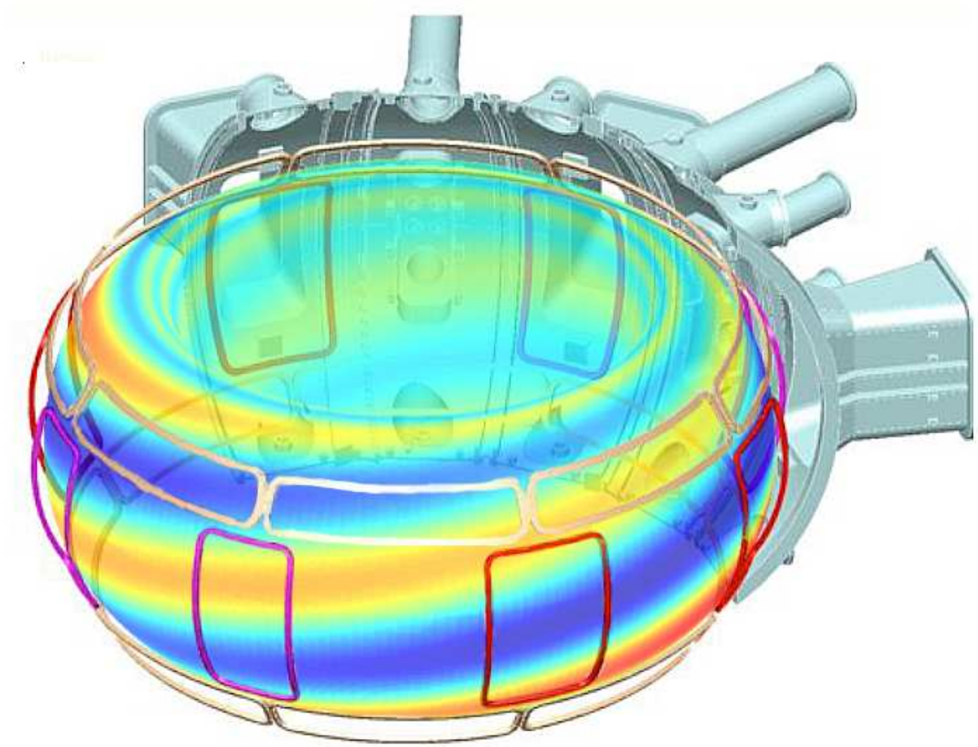


EFCCs: 4 coils, ex-vessel, n=1 or 2



ITER “ELM-coils” motivate ASDEX Upgrade enhancement

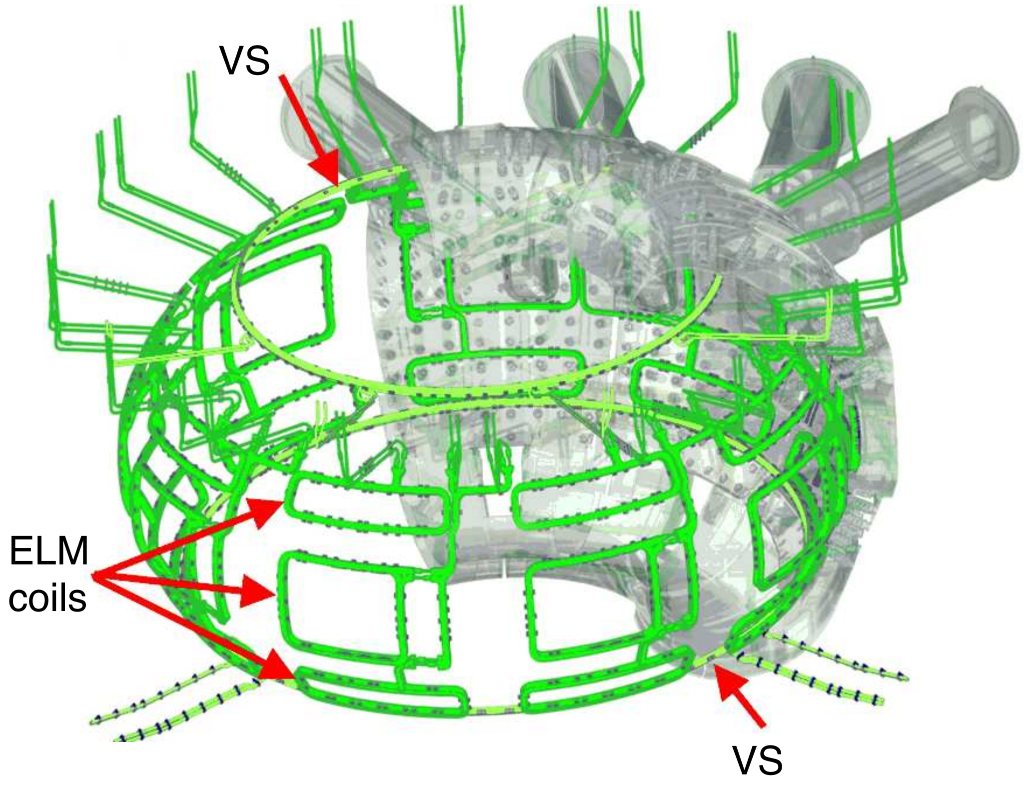
ASDEX Upgrade



3 rows à 8 saddle coils
in-vessel, low field side
individual current feeds, $n \leq 4$

W Suttrop *et al*, Fus. Eng. Des. 84 (2009) 209

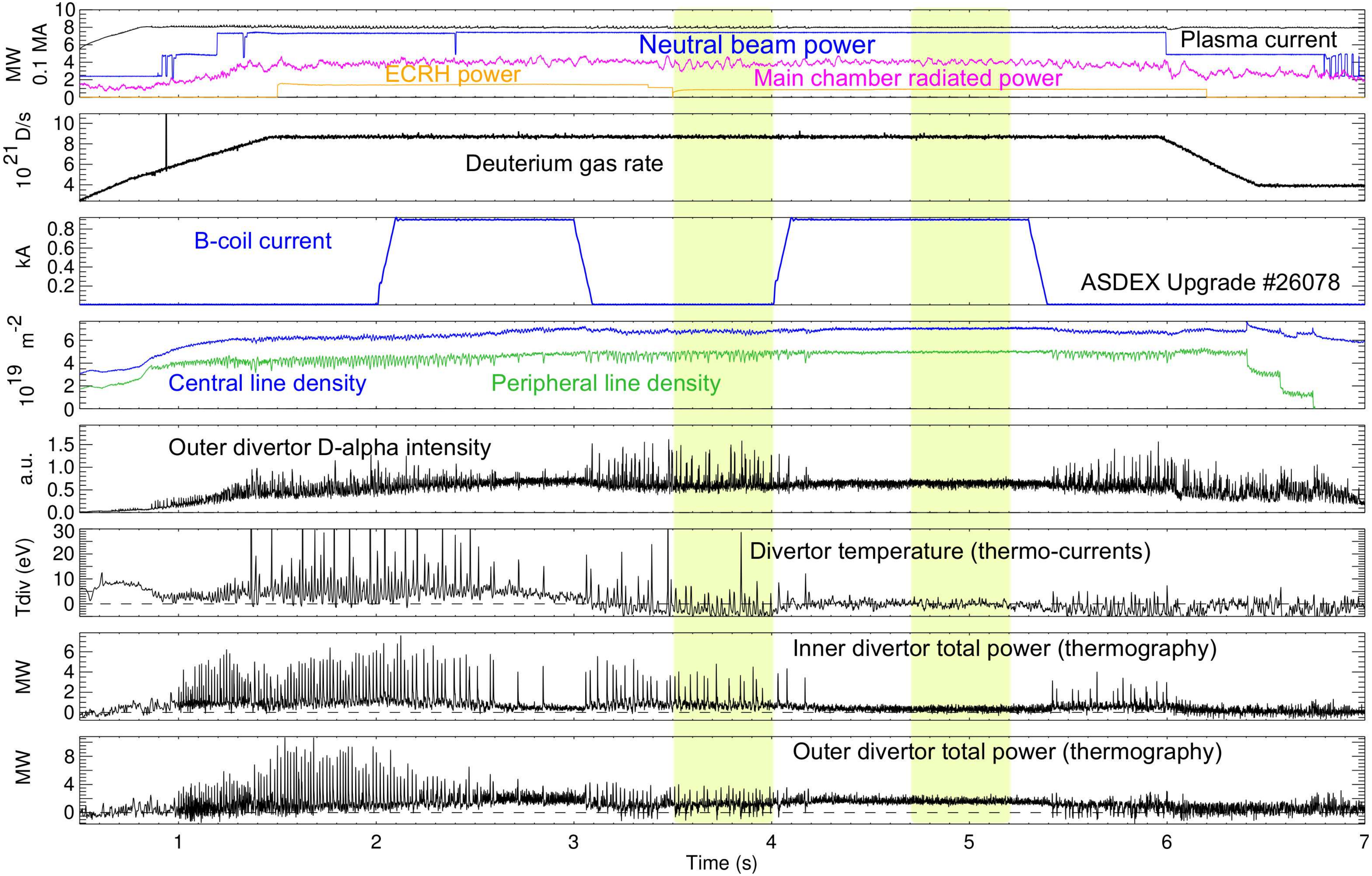
ITER



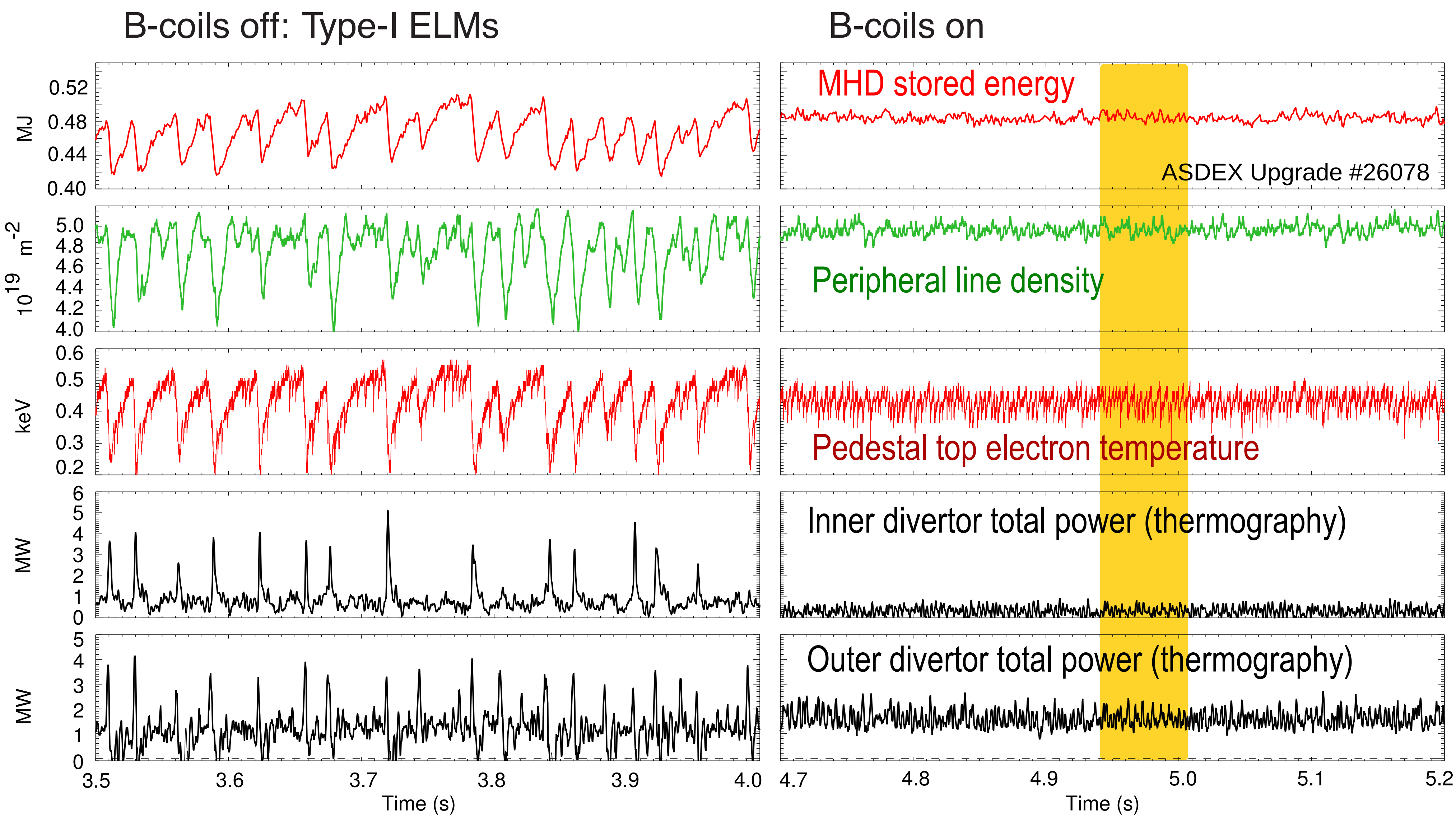
3 rows à 9 saddle coils
in-vessel, low field side
individual current feeds, $n \leq 4$

A Loarte, ITPA PEP March 2011

ELM-mitigation observed as B-coil currents applied



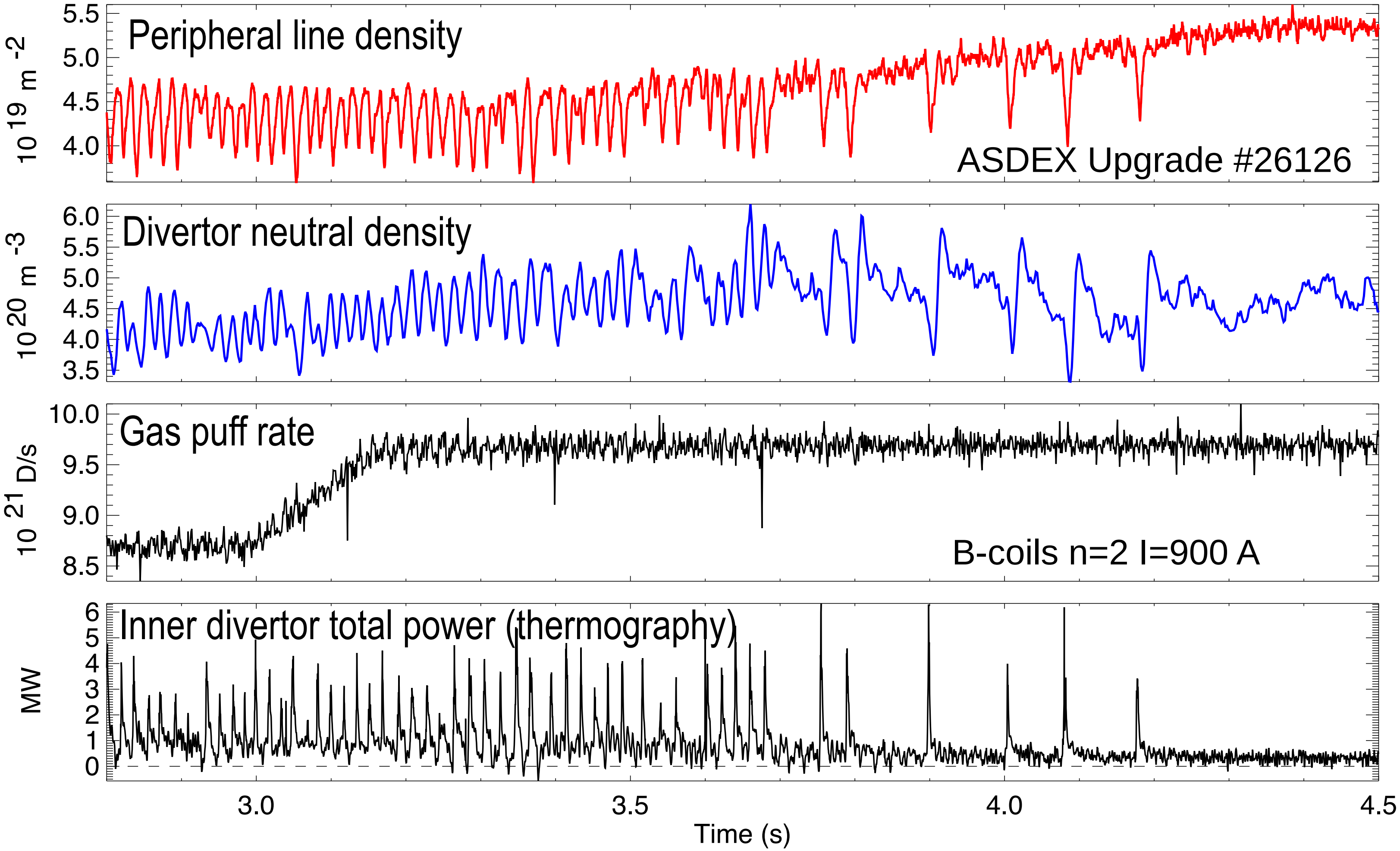
Comparison of Type-I ELMy and ELM-mitigated phases



Much reduced excursions of W_{MHD}, $\overline{n}_e$, $T_{\mathrm{e,ped}}$, P_{div}!

Particle confinement increases as type-I ELMs are suppressed

Slow transition induced by increasing plasma density:

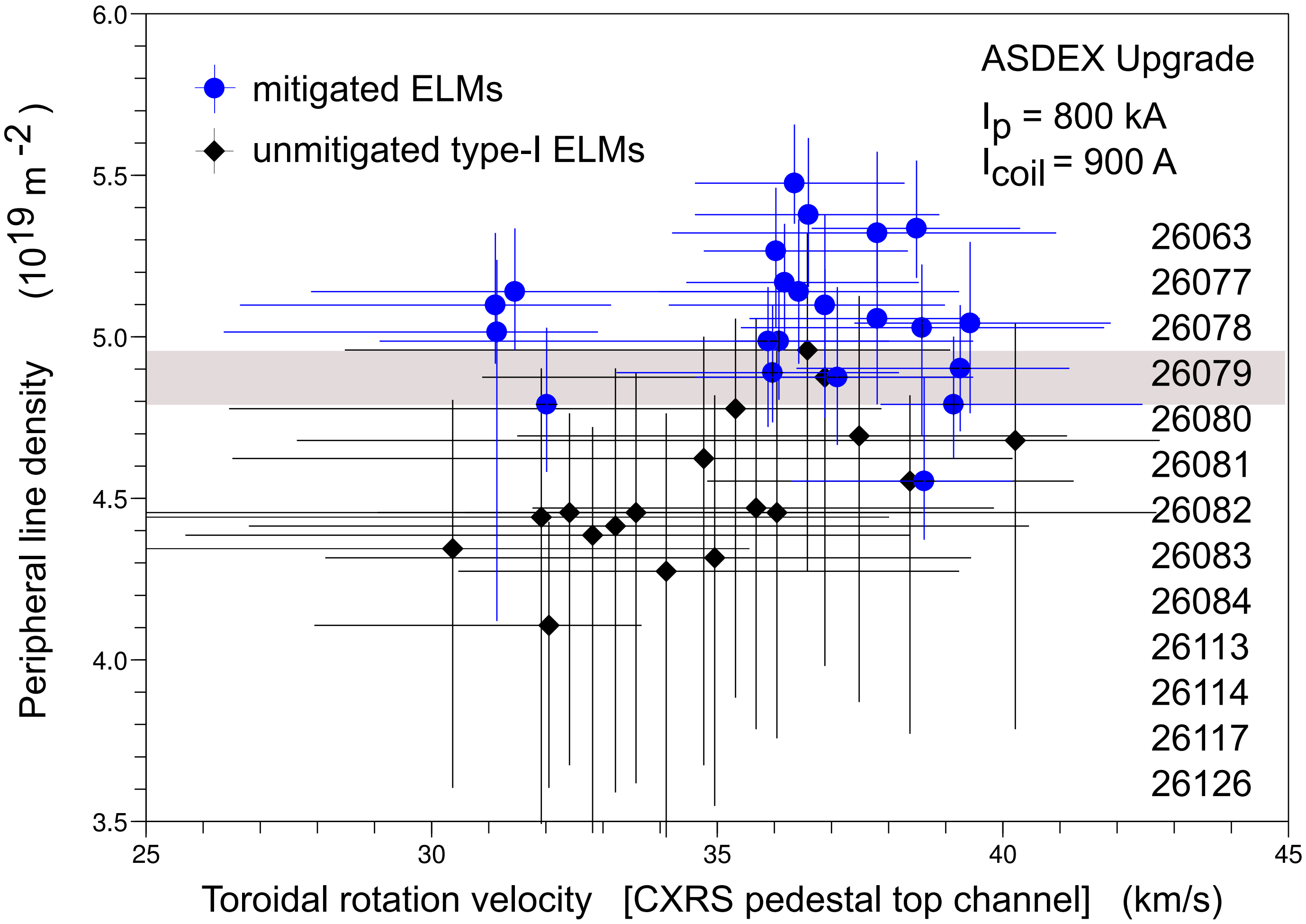


— Plasma density rises while neutral density drops

— Minimum plasma density required for type-I ELM suppression

Plasma density threshold, independent of plasma rotation

Plasma rotation varied by NBI momentum input + NBI / ECRH mix



ELM mitigation with all probed heating scenarios: $P_{\mathrm{NBI}} = 2.5 - 12.5$ MW, dominant RF.

Summary: ELM mitigation with magnetic perturbations in AUG

Large type-I ELMs replaced by small, irregular ELMs; reduced heat and particle losses.

— ELM-type transition, not a gradual evolution of ELM losses
— Power load reduction factor mainly determined by type-I ELM losses to compare with
— No price in confinement, density, impurity content
— Resembles DIII-D high collisionality regime [Evans et al. 2005]

Access conditions:

— **Insensitivity to magnetic resonance**
— **Density threshold**, depends on I_p; $(n_{GW} = 0.65, \nu^* \approx 1.4)$
still to disentangle which parameter critical

Outlook:

— Requirements for low collisionality ELM suppression/mitigation
— Broaden experimental data base, continue comparison with JET, DIII-D, MAST, NSTX
— Installation of additional eight coils 3+4.Q 2011, experiments 2012–

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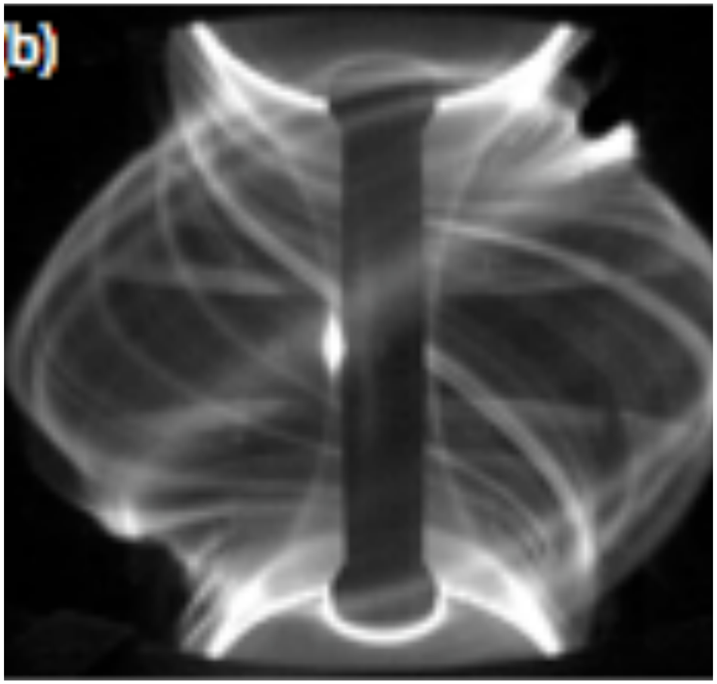

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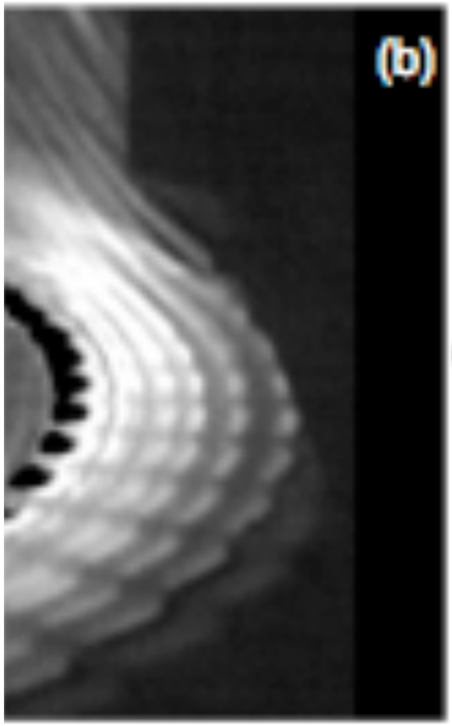
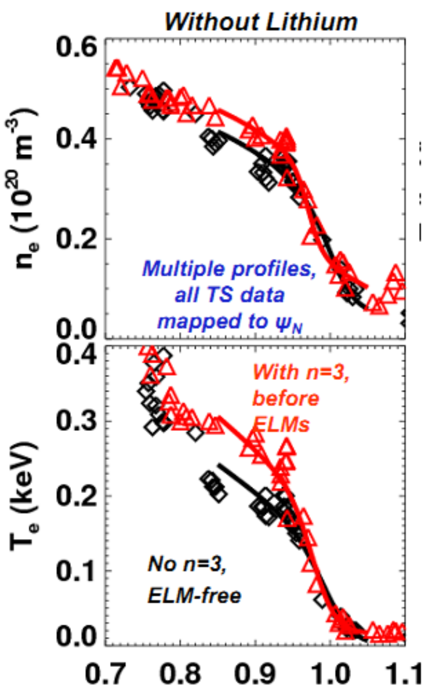
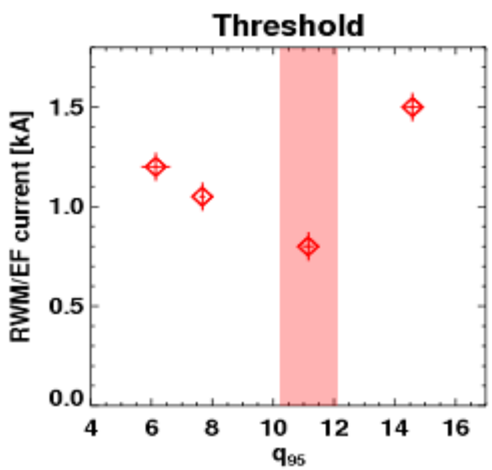
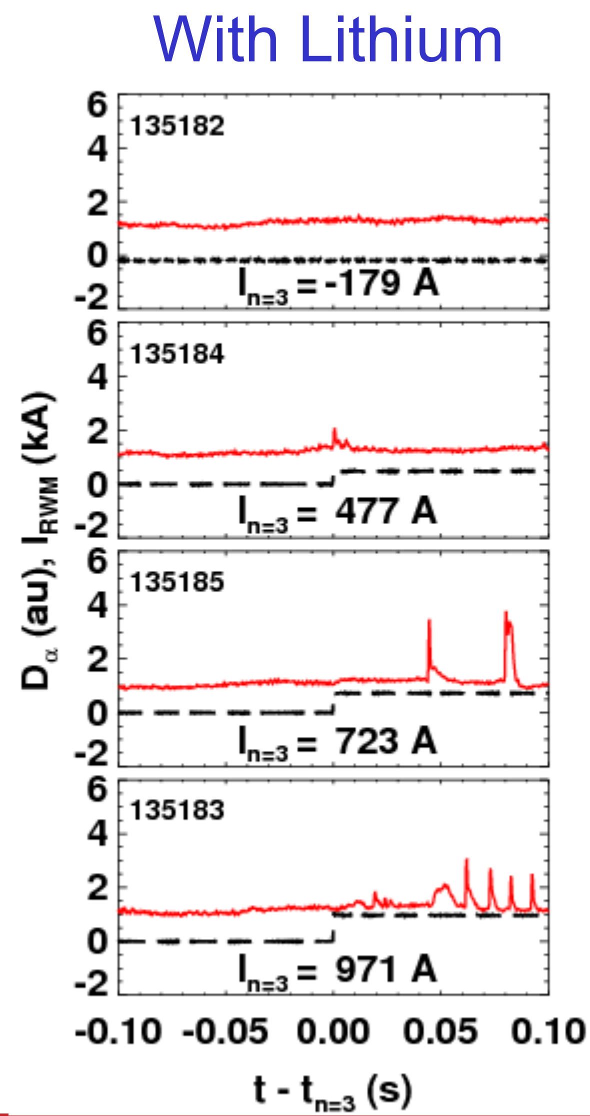


In NSTX, ELMs are destabilized above a threshold perturbation when DC fields are applied





- Above a threshold, n=3 field destabilizes ELMs without and with lithium-coated PFCs
  - ELM frequency increases with n=3 field magnitude
- n=3 field has little effect on n_e, sometimes (not always) *increases* Te
- Threshold 3D field for destabilization shows q_{95} dependence
  - Optimum window for ELM triggering at q_{95}~11



Magnetic ELM triggering has been applied to lithiumized ELM-free H-modes to control impurity accumulation

Typical behavior with Li wall conditioning

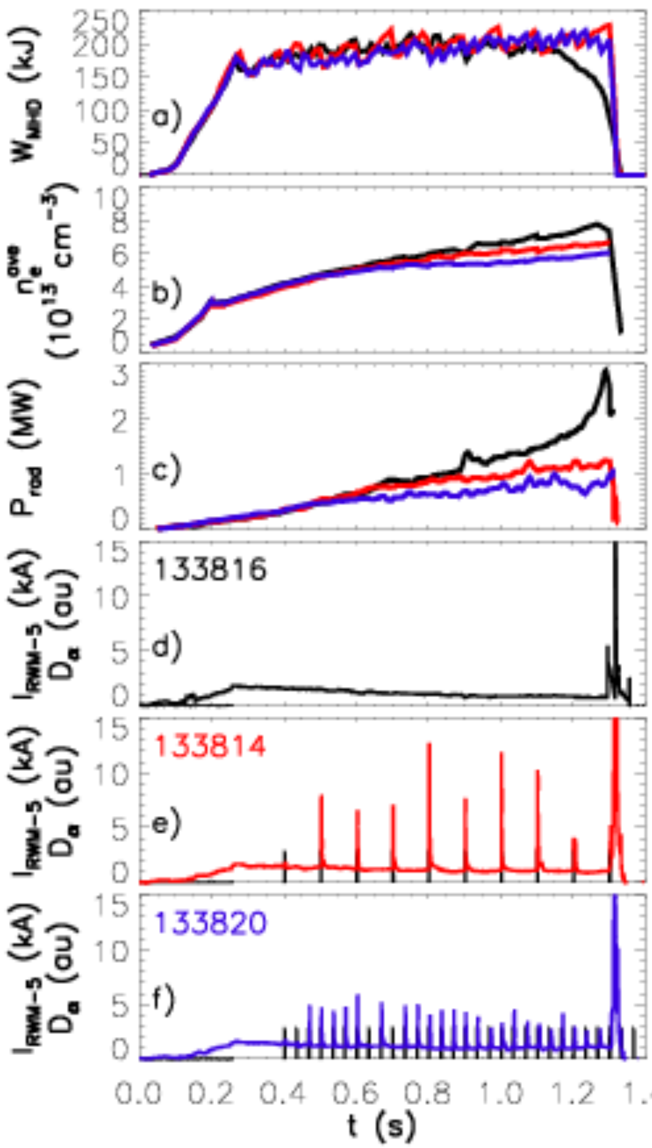
- ELMs suppressed
- P_{rad} ramps to >2 MW; P_{NBI} = 3 MW

Square wave of n=3 fields applied

- Fast pulses used rather than DC fields to reduce rotation braking
- 4 ms pulses, f=10/30 Hz, amp. 2.2 kA

ELMs can be triggered with full control over timing and frequency

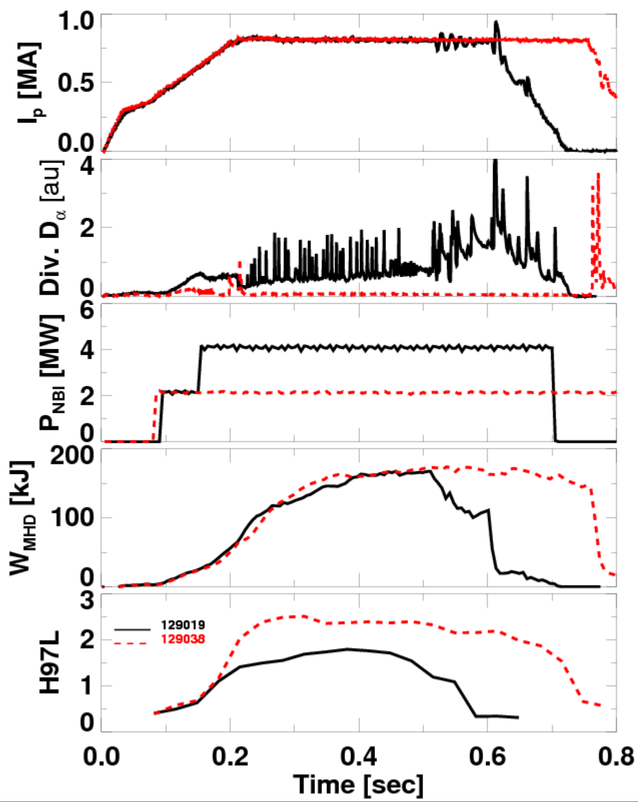
- Used here for discharge control, reducing n_e and P_{rad} ramp rate



J.M. Canik et al, PRL 104, 045001 (2010)

NSTX lithium coating experiments highlight the potential for controlling ELMs through the pedestal density profile

- With lithium, edge n_e gradient is reduced
  - Reduces pressure gradient/bootstrap current, eliminates ELMs*
- Indicates that controlling pedestal density profile can be used to control ELM behavior
  - Similar to DIII-D RMP experiments)



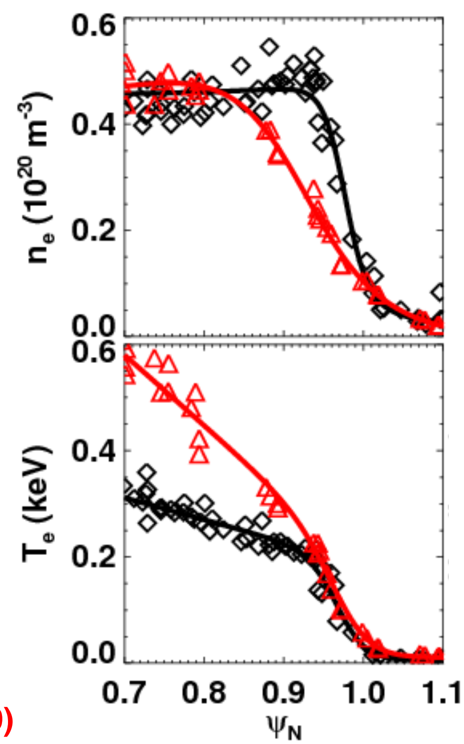
Without Li, With Li

ELM-free, reduced divertor recycling

Lower NBI to avoid β limit

Similar stored energy

H-factor 40%↑



*R. Maingi et al, PRL 103, 075001 (2009)

Selected ELM control references

- **ASDEX-Upgrade**
  - W. Suttrop, et al., Phys. Rev. Lett. **106** (2011) 225004
- **DIII-D**
  - T.E. Evans, et al., Phys. Rev. Lett. **92** (2004) 235002
  - K.H. Burrell, et al., Plasma Phys. Control. Fusion **47** B37 (2005)
  - T.E. Evans, et al., Nature Phys. **2** 419 (2006)
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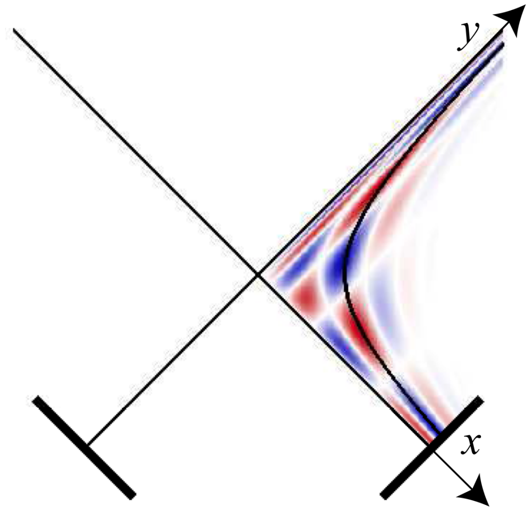
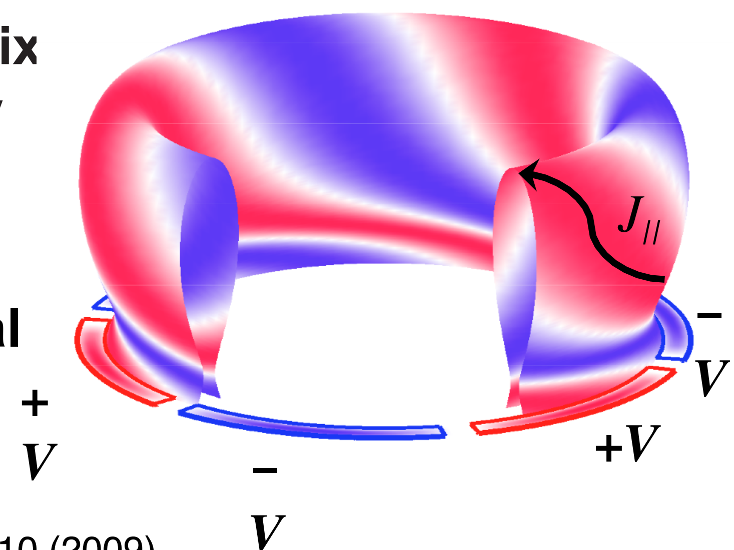
  - A. Kirk, et al., Nucl. Fusion **50** (2010) 034008
  - A. Kirk, et al., Plasma Phys. Control. Fusion **53** (2011) 065011
- **NSTX**
  - J.M. Canik, et al., Phys. Rev. Lett. **104** (2010) 045001
  - J.M. Canik, et al., Nucl. Fusion **50** (2010) 034012

- **Recent Review (does not cover new AUG results)**
  - Y. Liang, Fusion Sci.Tech. **59** (2011) 586

For a reactor, challenging in-vessel coil designs can be replaced by non-axisymmetric scrape-off layer current

- **Non-axisymmetric variations in the electrostatic potential drive both ExB convection and parallel current $J_{||}$**
- **SOL convection[1] can be used to spread particle and heat fluxes in the divertor**
- **SOL current[2] can be used to generate magnetic perturbations inside the separatrix that controls pedestal transport & stabillity**
- **Can be driven either by direct electrical biasing or by passive generation of toroidal divertor asymmetries**





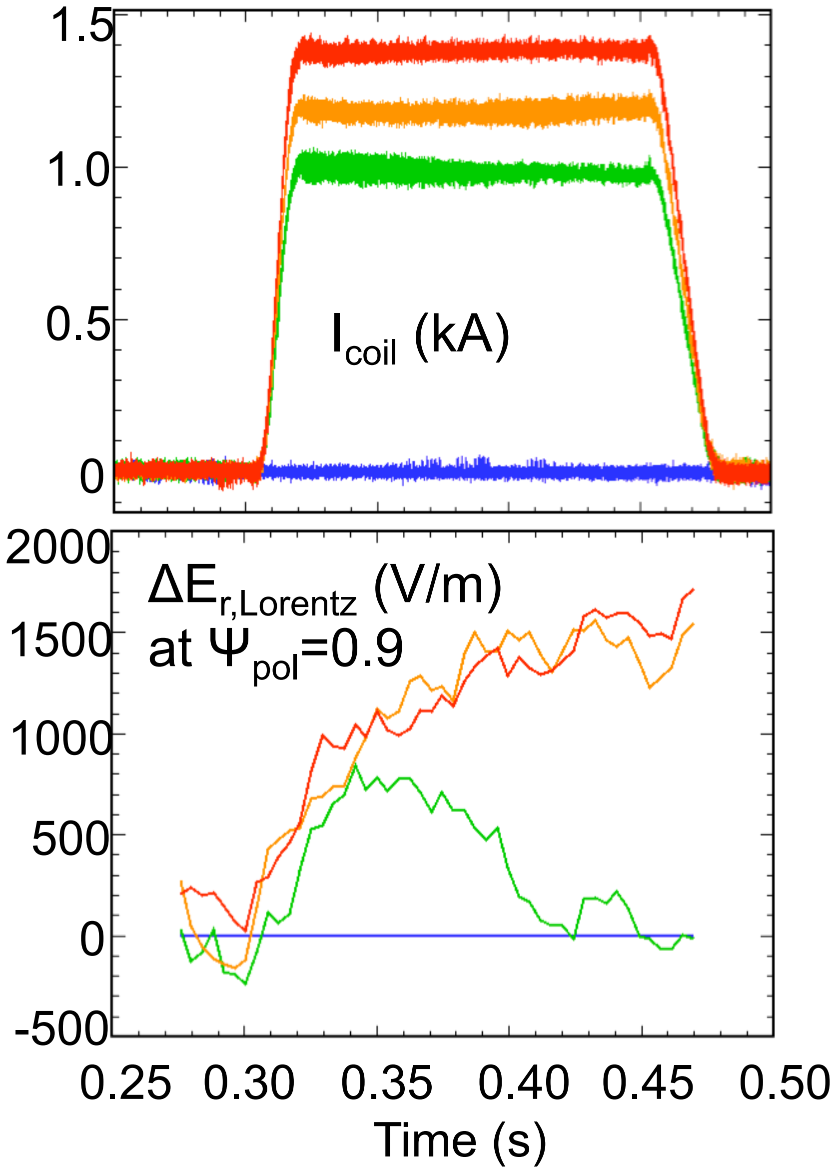
[1]R. H. Cohen and D. D. Ryutov, Nucl. Fusion **37** 621 (1997)
[2]I. Joseph, R. H. Cohen and D. D. Ryutov, Phys. Plasmas **16** 052510 (2009)

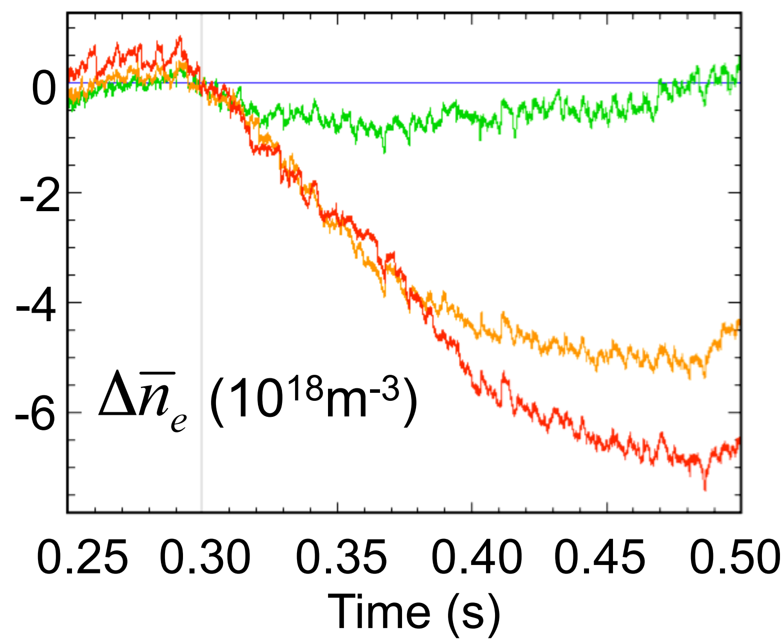
Additional Material …

L-mode results

- Visible increase in E_r due to its Lorentz part measured by Doppler spectroscopy on He: $E_{r,Lorentz}=v_{\theta,He}B_{\varphi}-v_{\varphi,He}B_{\theta}$

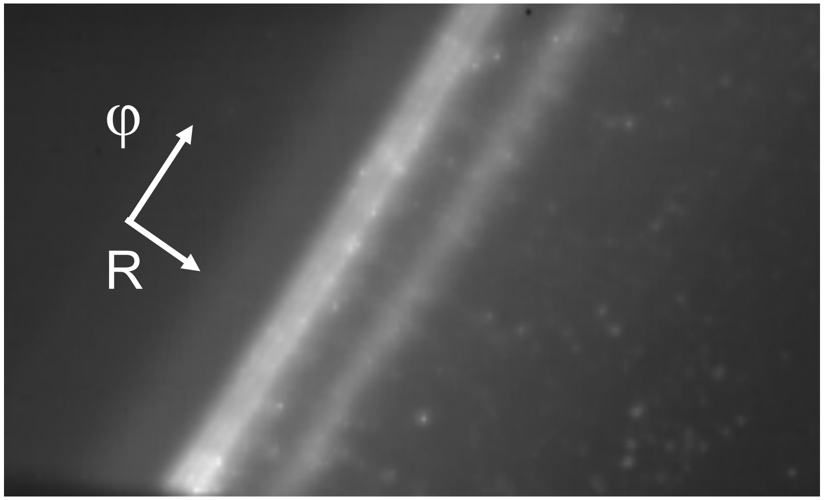
D. Temple, P5.191 on Friday

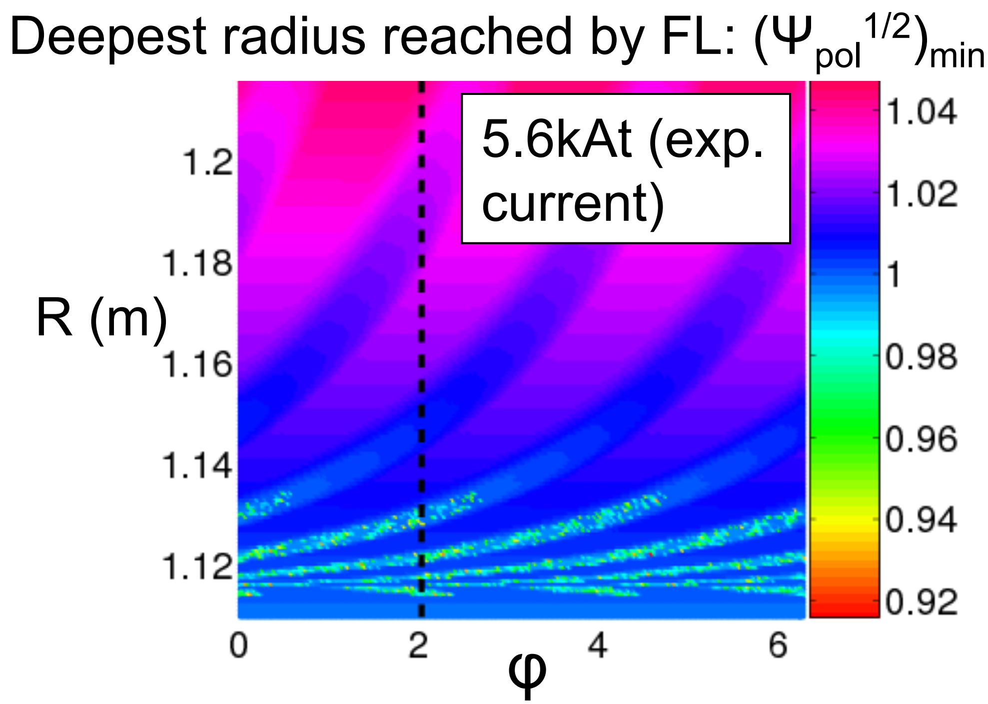




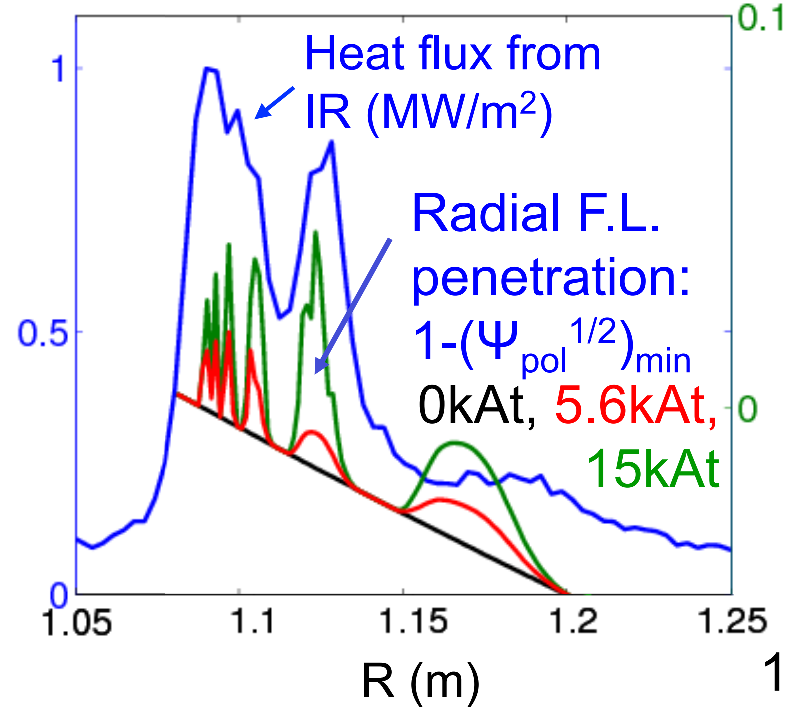
- ΔE_r~1.5kV/m
- ΔE_r>0 is expected in a stochastic field to preserve ambipolarity
- DIII-D with the I-coils (Burrell '05) and TEXTOR with the DED (Unterberg '07) have ΔE_r~10kV/m

L-mode results



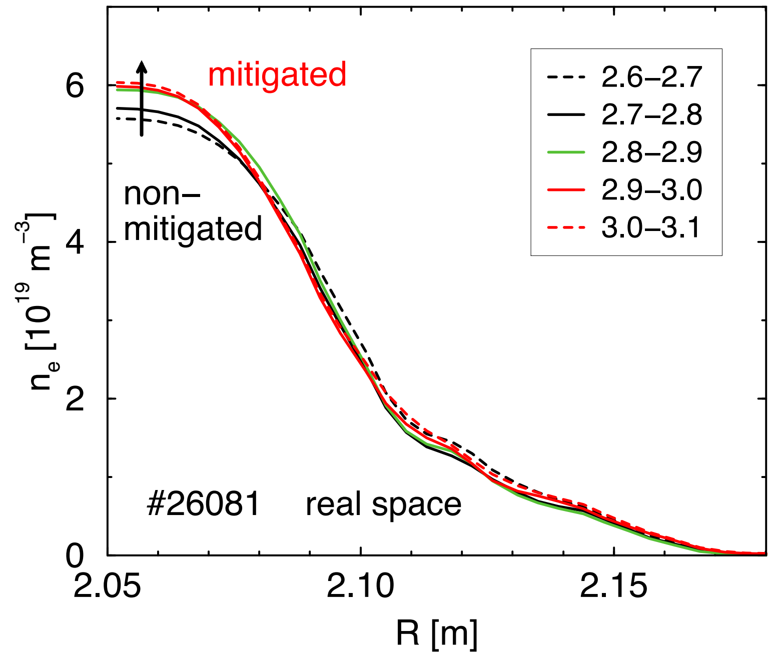


- Strike point splitting observed on infrared images of the outer target plate
- Vacuum modelling predicts a splitting
  - In spite of stochasticity, a coherent spiraling magnetic footprint exists
- Good match between measured heat flux profile and calculated field lines radial penetration



Summary of ELM mitigation phenomenology

- Type-I ELMs replaced by frequent small ELMs (not a gradual evolution of ELM losses)
- Divertor peak power reduction —
  Inner: Continuous detachment
  Outer: up to factor 4 (steady + ELM pulse)
- Particle confinement, pedestal density increase
- Pedestal temperature reduced by $\approx 10\%$
- Confinement / stored energy essentially unchanged
- Heavy impurity concentration (W!) not increased
- Z_{eff} not increased
- Minimum density requirement for ELM mitigation
- D pellet fueling: n $1.5 \times n_{\mathrm{Greenwald}}$,
  no ELMs triggered

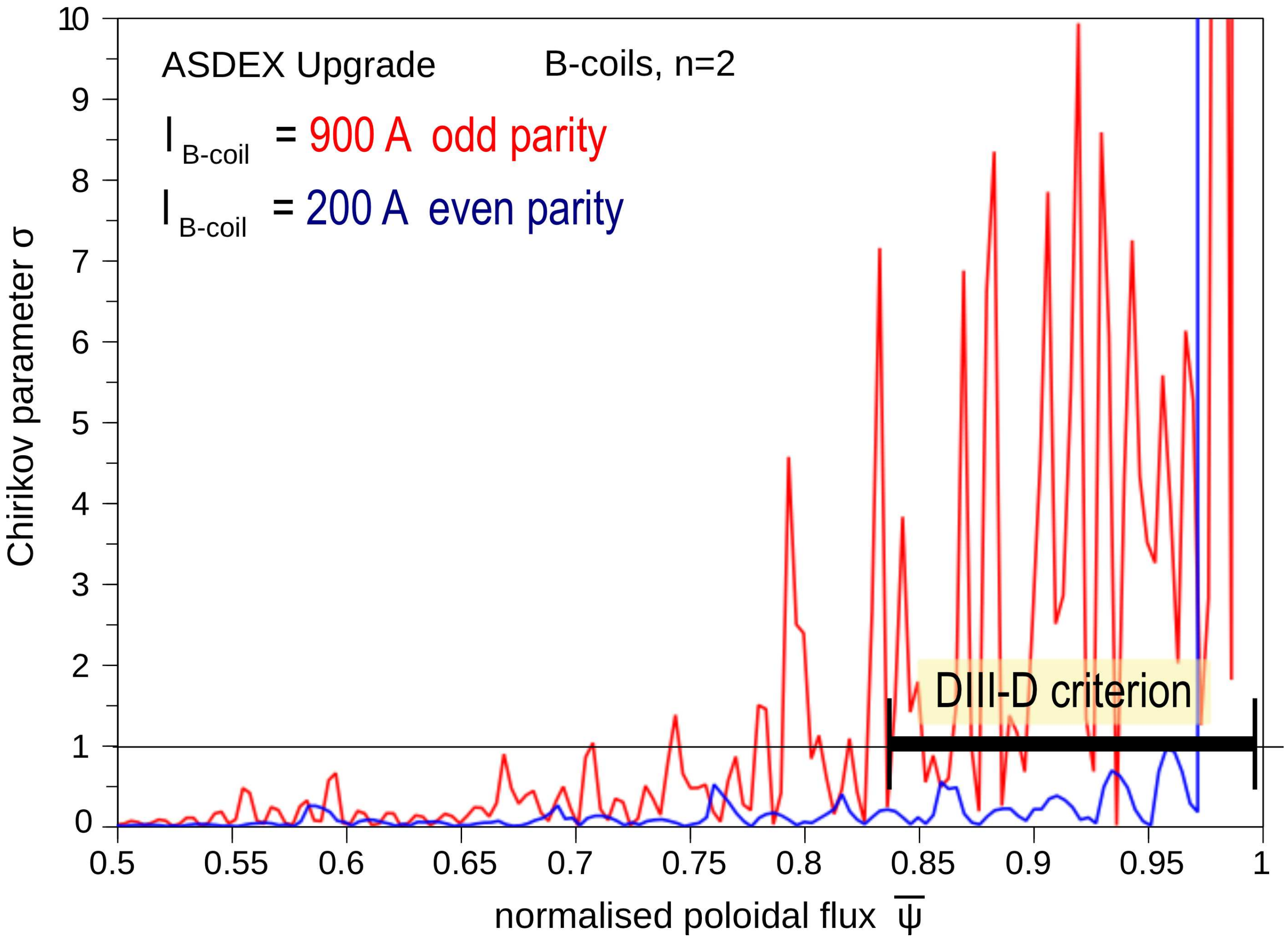


Pedestal profiles, Z_{eff}:
R Fischer, P1.072
B Kurzan, P4.048

Pellet fueling:
P T Lang, O.3.112

Chirikov parameter $\sigma > 1$ not a necessary condition

GOURDON field line tracing



$$\sigma \quad \frac{(\psi - \psi_0)_{\max}}{\psi_{m+} - \psi_{m-}}$$

Ergodic field where $\sigma > 1$

DIII-D criterion:

$\sigma > 1$ for $\overline{\psi} > 0.83$

[Fenstermacher et al. 2008]

ELM mitigation also with:

$\sigma > 1$ *only* for $\overline{\psi} > 0.97$

(even parity)

N.B.

Close to separatrix:

— $(\psi_{m+} - \psi_{m-}) \quad 0$

— open field lines always resonant

Chirikov parameter $\sigma > 1$ not a sufficient condition

Low q_{95}, low density attempt; Type-I ELMy H-mode